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PATTERNED GROUND AND RELATED FROST PHENOMENA IN SWEDEN

BY

JAN LUNDQVIST

STOCKHOLM 1962

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CONTENTS

Abstract: The paper presents a systematic treatment of the different types of patterned ground and their distribution in Sweden. Information is derived partly from published papers and partly from new observations. The types of patterns discussed are apparent from the list of contents. Their regional and vertical distribution is, when possible, studied by means of maps and profiles and their different modes of formation discussed. In combination with climatic maps the distribution and possible modes of formation indicate that the climatic conditions allow the formation of most types of patterned ground in most of Sweden. The limitations are mainly caused by edaphic factors. Only in a few cases (nonsorted polygons, palses, boulder depressions and possibly sorted and nonsorted steps) are the limits of a climatic nature.

Introduction

In spite of the rapidly growing literature on the phenomena related to frost action in the ground the regional distribution of different types of patterned ground seems to be little known in many areas. Much work has been devoted to such phenomena also in Sweden, but the different types and their distribution are unknown except within limited regions. Even comprehensive works, such as those of Troll and Washburn, refer to these things in Sweden only in very general words and even rather common features seem to be little known. The aim of this paper is to give a synopsis of Swedish works on patterned ground, especially concerning the types of phenomena, their distribution and interpretation.

The term "patterned ground" is here used in the sense of Washburn (1956, p. 824): "Patterned ground is a group term for the more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action". Thus the term is restricted to ground with some geometrical pattern; amorphous areas are not included. As the frost action also may result in amorphous types it may be appropriate to include also types lacking a symmetrical pattern in this description. The term "frost ground", commonly used in Swedish literature, is not quite adequate, either, because some of the pattern types are not necessarily a result of frost action. These facts account for the amplification of the title: "and related frost phenomena".

The paper is based on published work and also on a rich amount of unpublished observations collected partly by myself during the course of mapping in northernmost Sweden, Jämtland and Dalarna and during short excursions —

all in the service of the Geological Survey of Sweden.

A great number of observations were put at my disposal by Professor G. Lundqvist. Information was also contributed by mr K. Curry-Lindahl, superintendent of Skansen, and by mr K. Nilsson, Ph. Lic., from the activities of the Swedish State Power Board (Vattenfallsstyrelsen).

Much information was obtained also by studying photographs, in the literature as well as our own. Most of the observations and also part of this work was done at the Geological Survey. To this institution and to the persons mentioned I wish to express my sincere gratitude.

Previous research on the Swedish patterned ground

The real start of studies of patterned ground in Sweden seems to have been some lectures, held by J. G. Andersson (see Andersson, 1906, p. 107) when the attention of the geologists was directed to the relevant problems. Two small papers by A. G. Högbom (1905) and Sernander (1905) followed. Högbom's paper treated the problems of the oversaturation of clays. In this connection the so-called "boulder depressions" (p. 73) were described for the first time and correctly interpreted as frost phenomena.

Sernander introduced the conceptions solifluction and "flow earth" into the Swedish literature. He described a few types of patterned ground in the Caledonian mountain region which were different types of soil creep e. g., what is here discussed under the terms sorted and nonsorted steps. Sernander mainly considered the relation between solifluction and vegetation.

In a treatise by J. G. Andersson (1906) the solifluction and related phenomena mainly on Bear Island and the Falkland Islands were studied. Here also a first, brief summary of the observations from Sweden was given.

Svenonius (1909) discussed the conditions for the formation of the boulder fields in the mountain region. He considered these fields mainly formed by the disintegration by frost of the bedrock.

An important study was published by Bergström (1912). He showed that the patterned ground (of the polygonal type) not only belongs to the mountain region but may also be formed on lake shores in lower areas. He also studied some types of polygon patterns and made a first simple classification of them (p. 9). This, however, has not been generally accepted in its original form but in reality it does not differ very much from parts of other classifications.

Among the most important studies of frost action in the ground by Swedish authors are those of B. Högbom. His main treatise (1914) was based mainly on observations from Spitsbergen. In these works Högbom developed the multigelation theory, already suggested by G. De Geer (1904) in a discussion. The theory implies that during the freezing and thawing the ground refreezes several times each year due to fluctuations in the ground temperature. This was considered a condition necessary for the formation of patterned ground.

The hypothesis was criticized by J. Frödin (1914) and the criticism gave rise to an animated discussion (see B. Högbom, 1914 a, and the following discussion in the same volume).

Högbom's explanation of the formation of polygonal patterns is important: A concentration of fine fractions will attract moisture more than the surrounding soil. The maximum expansion thus will occur in such spots. At the expansion stones will be radially thrust. When the ground thaws and contracts the fine particles adhere to each other when they are pulled back but the stones will be left behind. If this process is often repeated it will result in a sorting of stones around centres of finer earth.

Among other results from Högbom's investigations may be mentioned that, like Svenonius (1909), he considered the boulder fields formed by disintegration of the bedrock. In this way even those fields containing or resting upon more fine-grained soil were formed. The fines should also have been formed by the same disintegration.

Högbom (1914, p. 308) also proposed a classification of the patterned ground. This is here further described on p. 9. As in other papers, however, his report on the regional distribution of patterned ground in Sweden is very general.

J. Frödin (1914, p. 208 ff.) made thorough studies of the patterned ground within a certain region in northern Sweden. Not only did he make the common, entirely morphological studies but also carried out comprehensive temperature measurements in the ground. These measurements clearly showed that the multigelation was of no effect, not even during the most rapid changes of the air temperature around the freezing point. From this fact, however, he drew the erroneous conclusion that frost action did not contribute to the formation of patterned ground. The observed phenomena were interpreted either as the result of soaking of the ground in water mainly from melting snow or as initiated on drying. The meltwater and snow drift contributed to the preservation of the drying cracks. In this way even typical frost phenomena such as stone polygons should be formed.

Almost contemporaneously with the last-mentioned works S. Johansson (1914) published a very important general treatise on the stability of the ground by different water content. He (p. 93 ff.) emphasized the fact that water will be enriched in certain types of ground during freezing. When a thaw sets in the released water will be an essential factor for solifluction.

Hamberg (1915) in his comprehensive works in the Sarek region also studied the frost action in the ground. He criticized Högbom's theory concerning the process at thawing. According to Hamberg the stones are prevented from returning to their original positions by finer material, collapsing under the stones while they are still fixed by ice at their base.

J. Frödin (1918) developed his earlier studies of patterned ground and now mainly studied the relations between such ground and the vegetation. He emphasized the important fact that frost action has the strongest effect where vegetation is thinnest. He described several types of patterned ground, some of which were not earlier observed.

B. Högbom (1926) took up his earlier investigations of frost action, this time mainly studying soil creep and its morphological effects. He also described a number of boulder fields in northernmost Sweden, and showed them to be formed directly from disintegration of the bedrock.

In the 1930's Beskow performed his very important works concerning the process of freezing in different types of ground and its effects on roads and railroads. His work from 1930 treated especially the patterned ground in the mountain region. An observation of essential importance is the formation of pure ice layers when material finer than 0.06 mm freezes. Thus an enrichment of water in such soils can occur which is a necessary condition for the formation of patterned ground. The volumetric expansion caused solely by freezing is too small to account for any large-scale reworking of the ground. The enrichment of water, however, may in northern Sweden cause a rising of the ground of half a meter or even much more. On thawing the water excess will promote soil flowage. Beskow also completed his work with many analyses of the mechanical composition of flow earths as well as of their water content.

Beskow considered three factors essential for the development of the ground pattern: the boulder content, slope and vegetation. Also the depth to the water table, velocity, frequency and depth of freezing and the influence of animals is of importance. According to the three first-mentioned factors Beskow classified the patterned ground (1930, p. 629).

Later (1935) Beskow developed his theories and tested them both experimentally and mathematically. He classified the frozen ground into two main types: the massive or homogeneous, and the ice-stratified or heterogeneous types. The type of freezing depends on the mechanical composition of the soil. Coarse material freezes homogeneously, fine soils will be stratified. This is of essential importance for the development of patterned ground.

This very important work of Beskow also appears in an English translation (1947).

G. Lundqvist (1944) mainly adopted Beskow's (1930) classification of patterned ground and also gave a very general summary of the main types known from the Swedish mountain region.

Later G. Lundqvist (1948, p. 7 ff., 1949) studied the orientation of the boulder material in flow earth and patterned ground. He found that as long as the boulders move freely they lie mainly in the direction of movement. When the movement is stopped against an obstacle or against the free air the bulk of the boulders turn perpendicular to the movement direction.

Boulder depressions were studied by G. Lundqvist (1951 b). For the first time their regional distribution was illustrated. Lundqvist also described the stratigraphy, which clearly shows that these features are formed by frost action in a ground mainly of till. Thus they differ from the boulder fields, described by B. Högbom (1926) and others. The earlier investigations had given a somewhat false impression that all boulder fields were formed directly from the bedrock.

In this work (1951 b, p. 509 ff.) G. Lundqvist also predicted the occurrence of fossil periglacial phenomena, such as patterned ground, in Scania. His prediction was later confirmed by G. Johnsson (1956).

A few smaller investigations of details of patterned ground may finally be mentioned: Sandberg (1938) especially studied the stratification and movement of step-forming flow earth. The stratigraphy under boulders, lifted up by frost, and the process of upfreezing were studied by Vilborg (1955). Jansson (1957) investigated the distribution of different types of patterned ground within a limited area. She was of the opinion that fossil and recent, arctic and subarctic types occur together in that area.

In this connection it may also be appropriate to mention Hörner's (1950) review of some modern investigations of periglacial and related phenomena. His discussion, however, mainly concerned American works.

A very brief review was also presented by Corbel (1956) in the Polish "Biuletyn Peryglacialny". This review, however, gives a somewhat misleading impression of the distribution of patterned ground in Sweden. Among others Corbel seems to believe that such phenomena are very rare in the high mountain region. Actually they are very common — if soil is available.

A more exhaustive, but nevertheless very brief review was published in the same publication by Rapp and Rudberg (1960).

The foregoing brief review only treated the patterned ground proper, that is the more or less recent phenomena of the mountain region above the timber line. The literature on other, special problems, such as fossil patterned ground and palses, is found in the different chapters, dealing with these questions. Studies by Swedish authors of patterned ground in foreign regions are not included in the review but reference to them is made in the text.

Systematic classifications of patterned ground

Most authors working with patterned ground describe several different types of pattern but only a few of them have attempted to arrange them in systematic classifications. Several different, more or less obvious principles have, however, been used for this purpose. As a rule the classifications are rather incomplete, considering only a few types of pattern, and do not always form a logical basis for discussions of the origin of the patterns.

The first to attempt a typological division of patterned ground seems to be

Meinardus (1912). He distinguished between four classes, which translated into English are: 1. Stone-stripes, 2. Stone-nets, 3. Stone circles, and 4. Boulder-fields with debris islands. There are also secondary forms, occurring within the patterns of the main types. Such secondary features are stone-festoons and stone-arcs. Obviously this classification is rather incomplete.

Bergström (1912) made the first Swedish classification, but this only concerned the more or less polygonal structures. He described three classes, only: 1. Bank polygons, 2. Knob polygons, and 3. Fissure polygons. The first type is a complex phenomenon. Knob polygons are formed at the welling up of water-soaked fines through the surface layers. Fissure polygons are the result of expansion and contraction.

B. Högbom (1914) used a modification of Meinardus' classification. His main types were 1. Stone-stripes (considered a form of solifluction), and 2. Polygons. Among the polygons he distinguished between: A. Stone-nets, B. Stone circles, C. Debris islands, and D. Cell-ground. (All terms translated from German.)

Beskow's (1930, p. 629) classification implied a great advance, giving us a system where all the main types of patterned ground in Sweden were included. This system was based on Beskow's already (p. 7) mentioned opinion of the factors, being most important for the typological development of patterns. In translation and somewhat re-arranged his classification is as follows:

Table 1. Classification of patterned ground according to Beskow

Increasing boulder content ↓

		Increasing slope →		
		Even	Moderate slope	Steep slope
Low boulder content	a	Earth hummocks	Hummocky steps, terraces	Steps
	b	Fissure polygons	Moss-covered ground: Miniature steps No vegetation: Amorphous flow earth	
Moderate boulder centent	a	Stone-bordered tufts	Stony, hummocky steps and terraces	Stony steps
	b	Stone nets (positive stone polygons)	Elongated stone nets, stone festoons	Amorphous flow earth, stone steps, superficial enrichment of stones
High boulder content	a	Stone pits (negative stone polygons)	Steps or hummocks with boulder front	Steps with boulder front
	b	Stone nets	Elongated stone polygons, debris islands with boulder front	Amorphous flow earth, sloping boulder fields, »Stone-Rivers»

a = Rich vegetation; b = Poor or no vegetation

G. Lundqvist (1944, Fig. 185—186; 1949, p. 336) adopted the same classification basis as Beskow and showed the following schematic picture of the main types of flow earth:

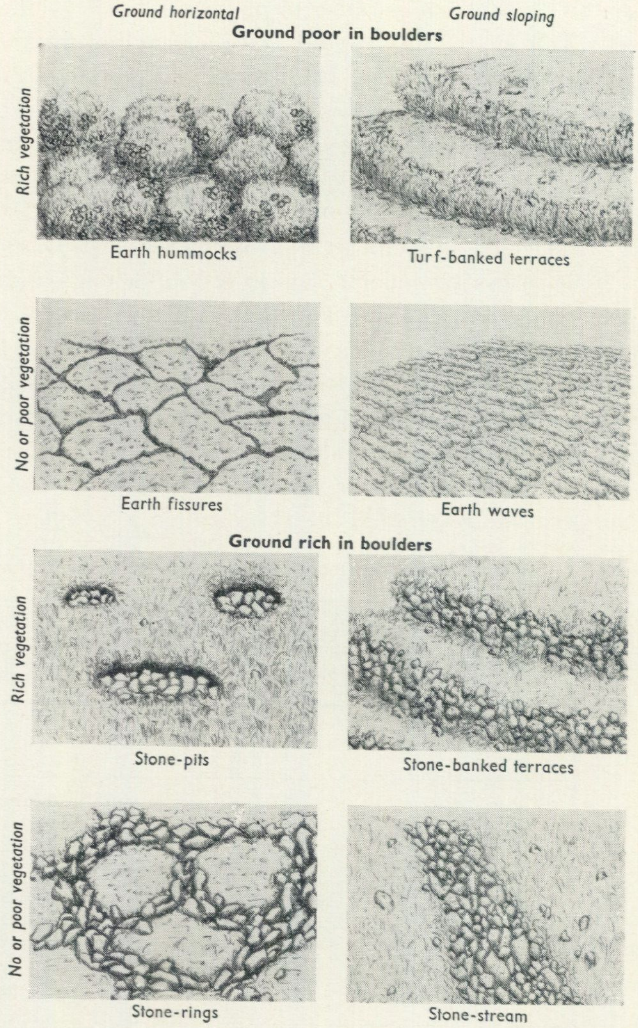

Fig. 1. Classification of patterned ground according to G. Lundqvist (1944, 1949).—From G. Lundqvist (1949, Fig. 1).

The classifications of Beskow and G. Lundqvist have the advantage that they include all the main types of patterned ground. However, more rare types are not included whilst other unimportant types occur. The classifications also may give a possibly false impression of a genetical system.

Steche (1933, p. 195) developed a classification, which is neither based on typological nor on genetical relations. The basis is the geographic—climatic distribution of the different types. Thus forms of patterned ground with no resemblances are grouped together: Group I consists of the subdivisions 1. Stone-streams, 2. Stone circles, 3. Stone-nets, and 4. Hummocks. To Group II belong 5. Palses, and 6. Taimyr polygons. Fossil patterned ground forms a group III.

This classification is less convenient for more detailed discussions of patterned ground and for surveys of such phenomena within limited areas.

An interesting classification was presented by Sørensen (1935, p. 64—65). He used as a basis the kind of material, the slope, and the snow conditions, resulting in differences in water supply. His system refers to the arctic types of pattern, but is also shown here as a comparison. It is translated mainly in agreement with the terminology used in this paper (see Table 2).

The classification implies some uncertain factors and may group together quite different forms. Thus it is not so readily applied to the subarctic phenomena.

Troll, (1944, p. 546 ff.) in spite of his very comprehensive studies, only divided the patterned ground in two main groups: 1. Structure ground, and 2. Amorphous frost ground. To the first group belong stone-circles, stone-nets, stone-stripes, earth-stripes, debris islands, and ice-wedge polygons. To the second belong earth hummocks, miniature peat hummocks, palses, string bogs, earth palses, flow earth steps and lobes, festoons, and boulder streams.

Troll's classification is in reality rather similar to Washburn's (1956, see below).

The two authors, however, did not use the same classification basis. This fact results in differences in the placing of certain types e. g., ice-wedge polygons and some flow earth steps.

Washburn (1950, 1956) introduced a classification based entirely on the geometrical character of the pattern and on the presence or absence of separation between boulders and fines. In this way the classes circles, nets, polygons, steps and stripes were obtained, each of them consisting of a sorted and a nonsorted subclass. The classification is thus entirely morphological and says nothing about the environments in which the different types occur — except that the classes steps and stripes occur on slopes, the others on almost horizontal ground.

Washburn considered an entirely descriptive classification preferable — in its turn it may help to develop a genetic classification. However, the classification is obviously rather insufficient — it cannot supplant other terms, to make descriptions more exact. Thus in many of Washburn's classes entirely different — morphologically as well as genetically — types are grouped together. This was also realized by Washburn. He proposed that terms like ice-wedge polygons and peat rings still be used but in a unique sense. Another disadvantage of the system, is, from a genetical point of view that genetically similar phenomena may be placed in different classes, depending on their environments.

Table 2. Classification of patterned ground according to Sørensen

		Heterogeneous material			Homogeneous material		
		Steep slopes	Moderate slopes	Even	Steep slopes	Moderate slopes	Even
Thawing to normal depth, not exceptionally late	Small water supply	Talus (Miniature stripes)	(Miniature stripes and nets)	(Miniature nets)	Amorphous earth lobes and »glaciers»	Flat earth lobes and elongated cell ground	Cell ground
	Rich water supply	Stripes	Stripes, elongated polygons	Stone polygons	Amorphous earth lobes and streams	Lobate terraces, elongated debris islands	Earth polygons (debris islands)
	Very rich water supply. Never drying	Boulder terraces, stripes	Stripes, festoons, debris islands	Stone-nets, debris islands with stone circles	Amorphous earth streams	Amorphous earth »glaciers», debris islands	Debris islands
Late thawing to small depth	Extremely wet, always excess of water	Boulder fields	»Pavements»	»Pavements»	Amorphous, wet earth streams	Amorphous, wet debris islands	Wet debris islands

As the following review will describe a large number of types within a limited area it seems most appropriate to use an entirely descriptive classification. The advantage of such a system is increased by the fact that the genesis of many patterns is still rather incompletely understood.

The use of a classification based on the milieu of the pattern types will in some degree anticipate the results of this compilation. Also in that way it will be very difficult to separate the types, because they sometimes occur together, in spite of their belonging to quite different classes.

For these reasons the descriptions here will follow Washburn's classification. As this is somewhat incomplete, however, it will be necessary also to use further descriptive terms to separate different phenomena within the same group. Even Washburn's system itself is not sufficient — there are several types of patterned ground that may not be included in his classes. Thus the system will be enlarged and some new classes added. Following Washburn the new groups are divided into a sorted and a nonsorted subclass. The new classes directly appear from the chapters in the following article.

”Frost regions” in Sweden

From the map, Fig. 3, it is seen that Sweden may be divided into different regions according to the existing types of patterned ground.

In the extreme north, north of Lat. 65° N in the Caledonian mountain range — in the following referred to as the Caledonides — and north of Lat. 68° N east of the range, there is a region where permafrost[1] occurs. The reports on permafrost in Sweden vary much. B. Högbom (1914, p. 374) stated that permafrost occurs almost everywhere in *regio alpina*. Hamberg (1904), however, analysed the temperature conditions for the existence of permafrost and came to the conclusion that it exists only in the highest mountains in the extreme north — where a soil cover is absent. But the water in the bedrock is probably frozen.

The question is not yet cleared up. Scattered observations of very deeply frozen ground from large works and borings in the north (see also B. Högbom 1914, p. 263) indicate that permafrost may exist within the zone marked on the map. The observations are not numerous, however, and it seems doubtful whether the permafrost is widespread. Ekman (1957, p. 29 ff.) gave a summary of all available data of permafrost. The area with sporadic permafrost found by him mainly coincides with the northern region shown in Fig. 3. Ekman also reported that double layers of perennially frozen ground are common. He made the important

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[1] The term permafrost, which is conventional and simple, will in this article be used instead of the linguistically more correct pergelisol (Bryan 1946). The Swedish word "tjäle" is often erroneously used for the same phenomenon. Even Bryan (1946, p. 635) first seemed to believe that this Scandinavian word means perennially frozen ground. Later (Bryan 1951) he corrected this error and gave a good review of the word tjäle and its meaning. The word simply means frozen ground—which in Sweden mostly implies annually frozen—or better "the frost in the ground".

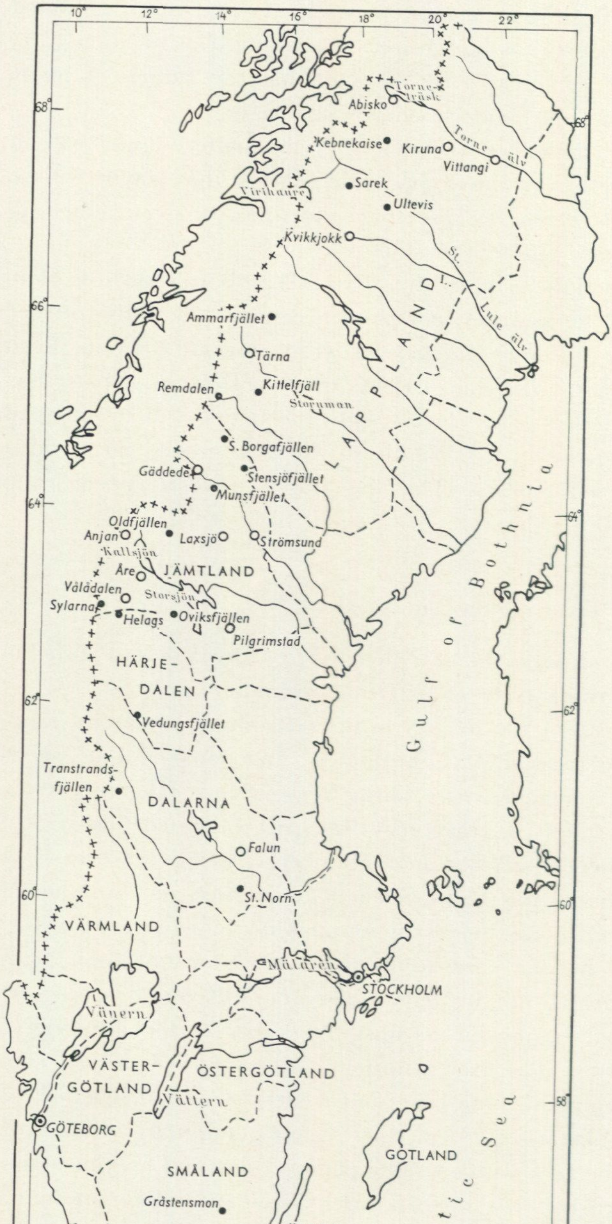

Fig. 2. Location map.

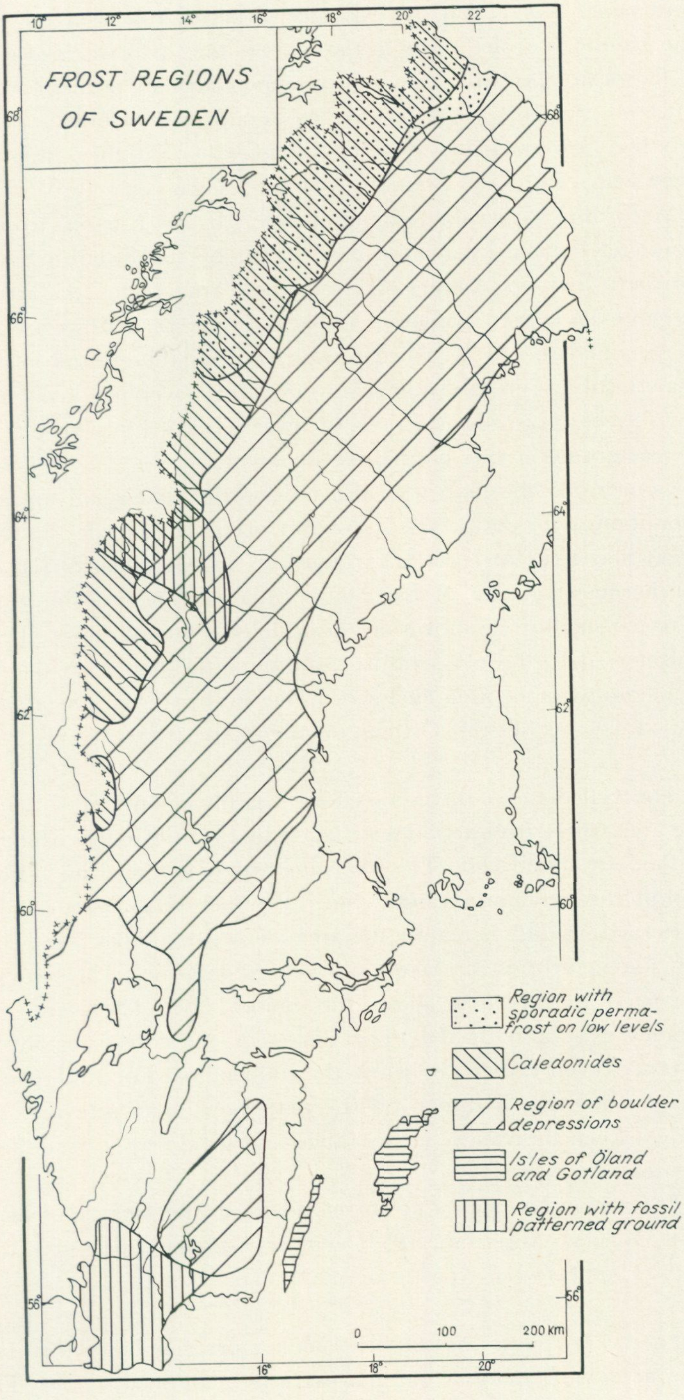

Fig. 3. Regional division of Sweden according to the type of frost phenomena in the ground.

statement (p. 44) that the existence of permafrost is merely due to the fact that the ground is cooled more in the winters than it is warmed in the summers.

Palses are probably the most common type of permafrost phenomena in the lowlands (p. 70). In the higher mountains the ground is possibly mostly frozen — there are glaciers and perennial snow — but the lower limit of a probable zone with continuous permafrost is not known.

According to personal communication by K. Nilsson, frozen ground is found now and then in excavation carried out by the Swedish State Power Board in northern Sweden. Among others in the Tärna region the ground is permanently frozen even in some valleys. Double layers of permafrost are also found here.

Attention should be called to the fact that the ground in some years does not thaw until late in the summer, even in the lower regions. Thus the ground may possibly be frozen over periods of several years. Only very accurate observations can determine if true permafrost is present.

Concerning the map it is also noteworthy that small areas of the type "high mountains with permafrost" probably occur far outside the marked region. Such areas may exist at least as far south as in Mt Helags (Lat. 63° N). Here the southernmost glacier of Sweden is situated. The possible permafrost areas are here too small to be shown on the scale of the map, however.

Referred to the temperature conditions the region in question approximately coincides with the area enclosed by the isotherm for a mean annual temperature of —1° — —2° C (cf. Östman, Wallén, Ångström, 1953).

The Caledonides themselves form an important region on the map. This is the area where frost action is strongest by far in Sweden. Many types of patterned ground are found here. The following article will deal mainly with the conditions within this mountain range. The mountain range, from the point of view of patterned ground, is mainly the area above the timber line (cf. Fig. 4) However, this statement must be taken in a very wide sense: The patterned ground is not restricted to the area above the timber line. The same types of patterned ground exist also in the upper parts of the forest region and in more rare instances even rather far below the timber line. For this reason the limit of the zone in question is drawn on the map even more schematically than the scale allows. Even the valleys in the range and its closest surroundings are included in the zone.

The timber line shows no correlation with the mean annual temperature (Östman, Wallén, Ångström, 1953) but is possibly connected with the isotherm for +11° C of July (cf. Ångström, 1953, map 7).

The lower country outside the Caledonides may be divided into several regions. The area with sporadic permafrost was mentioned above. The largest part of Sweden is the region of the boulder depressions, further described on p. 73.

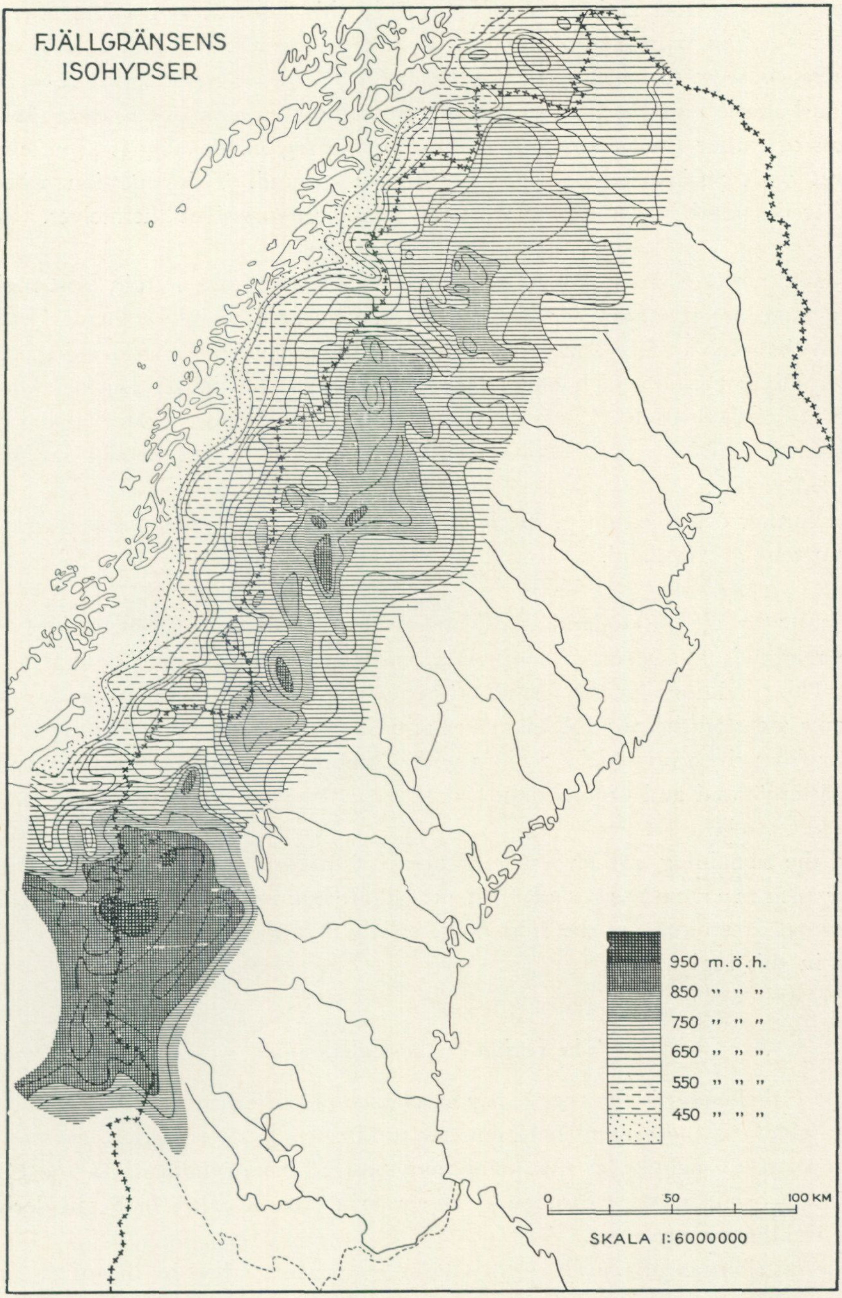

Fig. 4. Height of the timber line in Sweden and adjacent parts of Norway. Heights in meters above sea-level.—From G. Lundqvist (1943, Fig. 46).

Other signs of frost action are sparse within this zone. It is possible that this region is not an expression of the present climate. In most of Sweden the boulder depressions seem to be more or less fossil. On the other hand fossil ice-wedges, cryoturbulence and the like are not known from this area. Thus there are no proofs of earlier (periglacial) permafrost in the region. Possibly it represents a region with periglacially periodically frozen ground. This question will be further discussed in connection with the boulder depressions themselves.

Southernmost Sweden, Scania and adjacent areas, form a certain frost region. Here there are proofs of earlier permafrost. The area mainly coincides with a region that was ice-free and probably barren in front of the ice during the cool Older Dryas period which ended approximately 10 200 B. C. During Alleröd time (10 200—8 900 B. C.; cf. E. Nilsson, 1960) the climate became milder and periglacial activity ceased. Consequently the zone does not extend far N of Scania (p. 87).

As further described on p. 87 there may also be a zone with fossil periglacial phenomena in Jämtland.

Finally the Isles of Gotland and Öland are considered a special region on Fig. 3. The reason is the occurrence of extrazonal patterned ground (see further p. 85). The conditions for the formation of such phenomena ought to be the same in some areas on the Swedish mainland also. However, no occurrences are known so far from these areas (the regions with Cambro-Silurian bedrock for instance in Västergötland and Östergötland).

In the remaining, rather restricted areas of Sweden no patterned ground or other permanent signs of frost action are known as yet. Accidental and abnormal exceptions are the frost boils, briefly described on p. 84, which occur even in this region.

The region of the Caledonides

The Caledonides is the region par excellence of patterned ground in Sweden. Only seldom is the ground here entirely unaffected by frost action. It may be appropriate to mention at this point that most of the phenomena in the Caledonides — as in most of Sweden — occur on a ground of till or a soil derived from weathering processes.

The distribution of the different pattern types was studied by means of maps and profiles but only in a few instances were the observations numerous enough to give a good picture of the distribution. In most cases the regional distribution comprises the whole region. Maps are therefore published only when the distribution is limited to a distinct part of the region.

The profiles were constructed by plotting the observations in a diagram showing height above sea-level vs. latitude. For the sake of clarity also a very schematical contour of the mountain range itself is included in the profiles. This is the upper, continuous line in the profiles. The lower continuous line is the timber line which varies much from east to west, being highest in the central part of the range (Fig. 4; cf. also Smith, 1920, map 2). This variation is generally around 100 meters but may be as large as 200 meters. Thus the line on the profile is a rough generalization, showing only the dominant height. The fall of the mountain contour and the timber line in the south is not caused by a real sinking — the reason is simply that the mountain range curves westwards out of Sweden. Thus this part of the curves shows more marginal conditions than the rest of it.

The dashed line in the profiles marks schematically the lower limit of the boulder field zone (cf. p. 62), which also shows great variations from one mountain to the rest.

It should be observed that the observations on the maps and profiles do not exactly agree with each other. This is due to incomplete descriptions of the localities, as to location or altitude. Therefore the observations on the profiles are not always the same as those on the maps.

Sorted circles

The circular pattern types may probably be considered the initial forms of several other types, and they will consequently be treated first. The "circular" patterns are more or less isolated, rounded features. One type consists of rounded spots of fine material in surroundings of coarse, mostly boulder material. These are the "debris islands", a term used by Washburn (1956) and which is a direct translation of the German "Schuttinseln" or "Erdinseln". Another typ of sorted circle, opposite to the mentioned, is the "stone pit", a translation from Swedish used by G. Lundqvist (1949).

Debris islands (Fig. 5) may occur also on fine-grained ground, but according to the classification used here these phenomena belong to the class "nonsorted circles" and will be described as mud circles later. Here only the debris islands on boulder ground will be treated. This is probably not a logical separation, which is one of the disadvantages of the classification used.

Debris islands of the sorted type are probably widespread in the Caledonides. However, they are mostly described as "stone rings" or with other terms meaning sorted polygons. Therefore it is not possible to distinguish them from sorted polygons in the literature, and consequently it is also impossible to show their distribution on a special map or profile. Thus they are shown in Fig. 17 together with the sorted nets and polygons. Neither Beskow (1930) nor G. Lundqvist (1944, 1949) included the sorted and nonsorted circles in their systems. Probably at least the sorted ones are considered sorted polygons.

Fig. 5. Debris islands in a boulder field, 1050 m. a. s. -l., between Mts Rajvotjåkko and Svalaliesotjåkko, northern Sweden.—From J. Frödin (1914, Fig. 68).

The probable area of distribution of the sorted circles comprises the whole Caledonian range. They seem to be formed everywhere where the ground conditions permit it. The condition necessary is a boulder field, situated as a surface layer on top of a substratum, rich in fines and susceptible to frost action. A high water table, keeping the substratum moist, is also necessary and there must be no vegetation close by able to invade a newly formed spot of fine soil.

If these conditions are fulfilled they are probably sufficient to allow the formation of debris islands. The frost conditions seem to allow this formation even far below the timber line (p. 78).

Above the timber line I have observed debris islands at scattered localities in many parts of the Caledonides though not in the southernmost part. They also seem to occur at all levels where soil is available. The phenomena occur even in the extreme north where sorted polygons are less common.

Hamberg (1915, p. 596) proposed the hypothesis that the fine circle material was "pumped" up through the boulder cover by repeated freezing and swelling. Through this process the boulders are forced radially outwards. Washburn (1956, p. 841), however, considered this theory speculative.

Thus the exact mechanism of the formation of debris islands is not known. The occurrence of such phenomena even on ground where frost action must be rare (p. 78) makes it probable that another factor may be of importance, too. This is the weight of the boulder cover. When the substratum is saturated with water it has a very loose consistency and it seems rather improbable that it will be able to support the heavy load of the boulders. These will sink in the loose material, pressing it upwards. Where there are interspaces between the boulders the fines will break through the cover. This fact is only seldom observed but was mentioned by Taber (1930, p. 131). The cohesion between the fine particles will keep them together in larger units. That the cohesion in any case will be a factor of importance is demonstrated by the often strong convexity of the debris islands and by the fact that there is a sharp contact between boulders and fines, even if the boulders are large. The fines show no strong tendency to creep into the large interspaces between the boulders. As Fig. 6 shows the sorting is good even long before a regular pattern is developed.

Fig. 6. Debris islands on Mt Namåive, N of Kiruna. The sorting is good even if the islands are very irregular — they gradually pass into larger fields of fine material. — Photo by J. Lundqvist 1950.

The explanation proposed here does not account for the regularity of the debris islands. However, it is a matter of fact that, as regards these phenomena, the regularity is overestimated. The regular islands are the most conspicuous but actually rather irregular examples are common, too (cf. Figs 6 and 42). The irregular forms grade into larger fields with varying forms, as can easily be seen where the boulder content locally decreases.

Stone pits (Fig. 7) in spite of their common occurrence in Sweden, seem to be rather unknown. Even Washburn (1956, p. 827), after his thorough examina-

Fig. 7. Stone pit between Mts Santa and Tjårventjahke, SE of Vålådalen, Jämtland. — Photo by J. Lundqvist 1961.

tion of the pertinent literature has no clear idea of their true nature. The stone pits are also described in the Swedish literature as "negative stone polygons" (Beskow, 1930, p. 629) which, however, is an inconvenient term. This type of patterned ground does not always occur in groups, so that a network can be formed, and their shape is circular rather than polygonal. Therefore G. Lundqvist's (1944) term stone pits seems to be more convenient.

The stone pits are shallow pits, a few dm in diameter, with a floor of stones without fine matrix. A closer examination will show that the largest boulders are those at the surface. They rest upon smaller stones, downwards replaced by gravel and finally sand. The stratification clearly shows that a sorting by the frost has taken place.

As was pointed out by Beskow (1930) and G. Lundqvist (1944, 1949) the stone pits occur on rather level ground, rich in boulders, and with a rich vegeta-

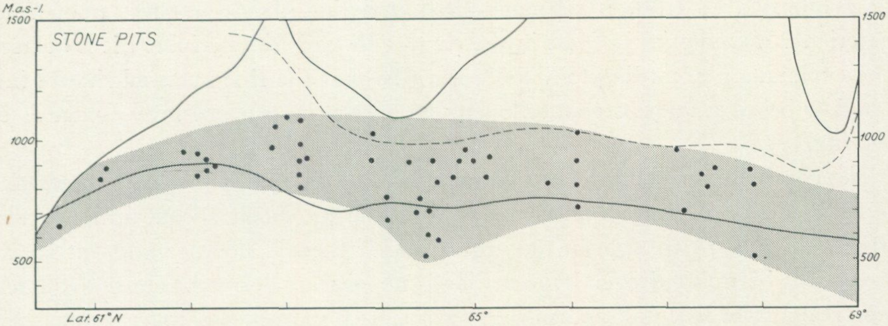

Fig. 8. The vertical distribution of stone pits in a profile along the Swedish Caledonides. The upper thick line marks the approximate upper surface of the mountain range, the lower line the approximate timber line, and the broken line the approximate lower limit of the boulder field zone. The zone with stone pits is shadowed.

tion. They have no exact counterparts on sloping ground, but morphologically they grade into sorted stripes.

The regional distribution of the stone pits covers the whole of the Caledonides. The vertical distribution (Fig. 8) seems to comprise mainly the lower part of the region above the timber line, and the uppermost part of the forest region. Occasionally, when the general conditions are favourable, they are formed even on much lower levels. In Jämtland they were observed as low as about 500 meters above sea-level (between Lakes St. Sjouten and St. Jougdan). It is noteworthy that this is in the same region where sorted and nonsorted polygons (p. 36 and 43) occur at abnormally low levels. A locality with extraordinarily low occurrences of stone pits was also described from Mt Ransby Gillersberg, northern Värmland, by J. Lundqvist (1958, p. 119, 1958 a, p. 49). This mountain hardly reaches the timber line and the stone pits occur on a level of about 640 meters.

The upper limit of the stone pits seldom exceeds 1 000 meters. Probably this limitation is caused by edaphic conditions. Above the limit vegetation is sparse, the freezing up of stones will occur over larger areas and small features like stone pits are not usually formed.

Genetically there are probably different types of stone pits. Rydquist (1960, p. 71 ff.) considered them parts — corners — of sorted polygons. In this case they would be formed by the same circulation process that is involved in the formation of the sorted polygons. If the ground has a too low boulder content the boulders are not sufficient for the formation of whole polygons. Only in the corners where three or four polygons come into contact will the boulders be enriched enough to form a pattern. Thus scattered spots of stones are formed. This, however, must be a rather special case.

The more common type of stone pits was investigated by Vilborg (1955) and Williams (1959 a). Vilborg's description of the stratigraphy of the material below stones uplifted by frost, is relevant. He found that the stones rest upon finer material. This material is finest in the centre; towards the periphery it is coarser. The explanation according to Vilborg must be that the fine material slumps into a hollow below a larger stone, following an expanding surface layer upwards on freezing.

The condition necessary for the formation of a stone pit is that a concentration of stones develops. One boulder makes no stone pit. Such a concentration may arise if there is a bare spot in the vegetation. If there is no vegetation at all the stones will be uplifted over large areas — no pits are formed. Thus a coherent vegetation cover is almost necessary. Towards bare spots in this cover the boulders will move during freezing.

The bare surfaces may be either of the type "nonsorted circles" (see below) or waterfilled hollows. The water keeps the hollows free from vegetation. Probably this is the most common type — indicated among others by the fact that the stone pits themselves are often waterfilled.

Williams (1959 a), however, considered scars of wind erosion to be the most important condition for the formation of stone pits ("stony earth circles"). This is a factor, the importance of which for other types of patterned ground was emphasized even earlier by J. Frödin (1918, p. 21—27). In the special case of the stone pits, however, wind action is probably not of essential importance — except in certain regions. The vegetation in the typical stone pit areas is of a thick type, not easily scarred by the wind. Where wind erosion is strong, stone pits are not common.

Williams also was of the opinion that two other factors are of essential importance, namely a thin snow cover and a soil, susceptible of frost action. Of course the last-mentioned factor is necessary but the snow cover is probably of secondary importance. It is essential only that there is not too much snow when freezing occurs or that the snow is not thick enough to prevent the transport of heat from the ground to the air. The occurrence of stone pits even in depressions where the snow cover is often thick indicates the correctness of this statement.

Observations from outside the Caledonides indicate that not even irregularities of the aforementioned types are necessary for the formation of stone pits (p. 80). Under favourable circumstances it is probable that stones may be enriched in shallow holes even in quite homogeneous ground.

Nonsorted circles

The only type of nonsorted circles observed in Sweden are exactly similar to the debris islands described above. Only from the surroundings is it possible to distinguish the two types. The term debris islands demands a coarse, mainly bouldery surrounding. The nonsorted circles are surrounded by soil of a similar type as themselves. Washburn (1947, p. 99) proposed the term mud circles for such features, which will be used in the following as a simpler and more descriptive term.

The mud circles seem to be almost entirely overlooked in investigations of Swedish patterned ground. They are not even included in the comprehensive classifications of Beskow (1930) and G. Lundqvist (1944, 1949). Probably, however, some of Bergström's (1912) descriptions refer to mud circles. J. Frödin (1918, p. 22 ff.) gave a more thorough description and interpretation. Photographs confirm that his descriptions refer to mud circles.

The mud circles (Fig. 9) are spots of bare soil, which break through an otherwise coherent vegetation cover. Their surface has mostly a clayey appearance. This is somewhat misleading, the material being rather unsorted and consisting of almost the same proportions of all fractions (Fig 11). As Fig. 10 shows, the material can, however, be much coarser. Even a coarse gravel can break through the humus and vegetation cover and even through a peat cover. In some instances one should rather describe the phenomena as sorted circles, because the circle material is then distinctly coarser than the surrounding surface material. Genetically this type must be the same as the nonsorted circles proper and as there are all transitions they are here described together with the mud circles. The conditions demonstrate a disadvantage of Washburn's classification.

So does the mesh of these phenomena. It is true that the ideal mesh is circular but too much emphasis must not be laid on the word circle. Other forms are common too. I have seen angular types, even rather perfectly rectangular and they may also be more or less complex, which, however, is less common. Washburn (1947) consequently distinguished between mud polygons and mud circles. At least in the Caledonides there is no limit observed between the types and they will therefore be treated together.

The mud circles often occur quite isolated but may sometimes form larger groups. Even in groups they are sparsely situated but naturally enough all transitions to close networks — nonsorted nets — occur. J. Frödin (1918, Pl. III) showed one example.

The mud circles proper belong to level ground. On slopes they have a correspondence that is, however, not at all circular. The rather liquid mud is likely to form a more or less horizontal surface. Thus, on a slope this surface will be extended along the contours — the pattern becomes terrassed. Downhill the mud surface is bordered by a low ridge of vegetation. Therefore the pattern might be called "turfbanked terraces" Antevs (1932). This term, however, was in Sweden used by G. Lundqvist (1949) as a synonym for nonsorted steps. A better term is therefore "mud terraces". A noteworthy feature is that the terrace surface, even if flat, may actually slope e. g. on Mt Grofjället and some mountains near Vålådalen, all in Jämtland (Fig. 12). Thus a transition is formed to the "nonsorted inclined steps" (p. 52).

Fig. 9. Typical mud circle near Lake Resemejaure, Mts Oldfjällen, Jämtland. — Photo by J. Lundqvist 1960.

It is noteworthy that the material in the centre of a mud terrace can break through the turf-bank and form a stream of small stones (cf. Antevs, 1932, Fig. 25). In this way transition types to sorted stripes are formed. This feature seems to be especially common among the miniature forms (cf. p. 68).

Information about occurrences of mud circles are too few to allow an exact description of their regional distribution. Therefore no map or diagram is shown of this pattern. The observations are most abundant in the northernmost part of the Caledonides. J. Frödin's aforementioned observations are from this district (Lule Lappmark) and I have personally seen mud circles in the area W and N of Kiruna. Further south they are reported from Mt Storfjället, Tärna, (Bergström, 1912) and I have seen them at scattered localities in Jämtland.

The reports seem to indicate a distinct vertical distribution: In the north, mud circles occur between 500 and 900 meters above sea-level. In Jämtland they belong to moderate levels above the timber line, especially around 1 000 meters. This distribution may be apparent, only, due to an insufficient number of observations. However, it may also have significance. The mud circles probably require rather low temperatures as indicated by their absence at lower levels in the south. They also require a coherent vegetation and humus cover — if this is absent other types of frost ground will be formed. This may explain the absence of mud circles on high levels with more sparse vegetation.

Bergström (1912) was of the opinion that mud circles were formed through

Fig. 10. Mud circle of gravelly material breaking through a thin peat cover, E of Mt Njuotjamavardo, N of Kiruna. — Photo by J. Lundqvist 1951.

a movement upwards of random concentrations of fines in the ground. By a large absorption of water they expand and force themselves through the surface layer. As J. Frödin (1918, p. 24) pointed out this hypothesis does not account for the lack of sorting in the mud circles. The most important process is, according to him, that freezing of the ground occurs earlier, and therefore also to a greater depth, below thin and consequently less isolating parts of the vegetation. Such spots will be raised relative to the surrounding ground. When the process goes on

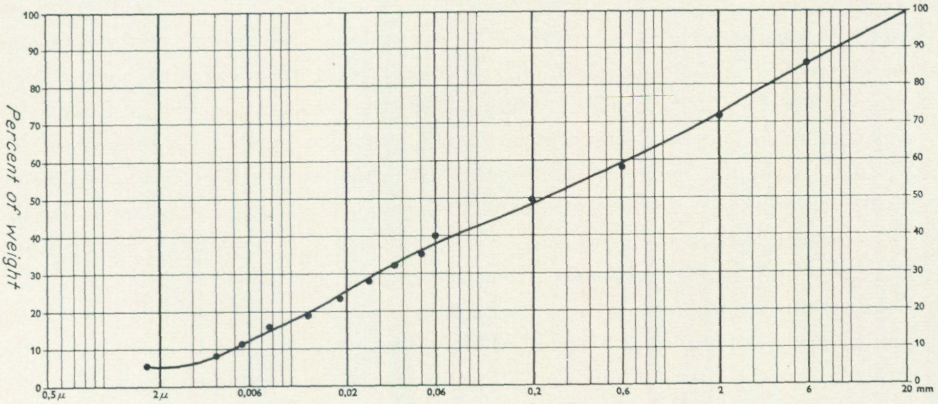

Fig. 11. Cumulative frequency diagram of the material in the mud circle in Fig. 9.

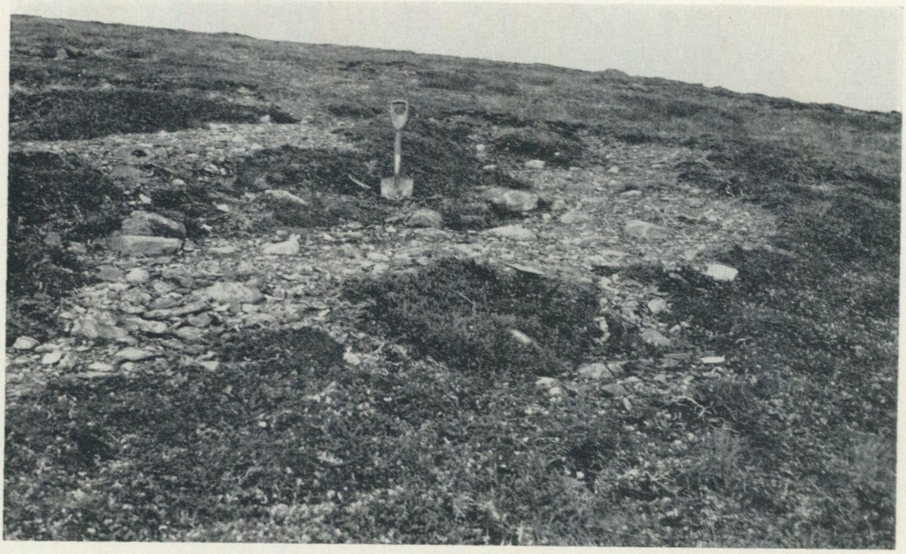

Fig. 12. Obliquely sloping mud terraces with wind-eroded surface, Mt Grofjället, Jämtland. — Photo by J. Lundqvist 1960.

wind erosion and other factors will make the vegetation cover still thinner and the process is accelerated.

In the light of Johansson's (1914) and Beskow's (1930 and others) work the mud circle formation is still better understood. Concentrations of fines will take up water from below and their expansion will therefore be still greater. They are thus able even to break through a coherent vegetation cover.

However, the assumption of concentrations of fines is not necessary. Frödin's (1918) opinion gives evidence for this. Where vegetation is absent frost action in the subsoil will be greatest. The expansion due to freezing and water absorption will thus be greatest where there are scars in the vegetation. Such scars may be formed by wind erosion, animals and other agents. This explains the fact that mud circles often occur isolated. Only where conditions are especially favourable will they form groups. I observed a relevant instance on the flat summit of Mt Välliste, Jämtland. Between the summit cairn and the hut the ground is scarred by the tramping of numerous tourists. Here mud circles are common. In the surroundings, where the ground is similar but where not so many people walk, it is more undisturbed and mud circles are lacking.

As Frödin pointed out, it is not necessary to assume a considerable distance of transportation of the mud material. This is shown by the lack of sorting and the similarity to the surrounding soil. However, in certain instances some transport may take place. Frödin himself described how the material from a mud circle may well up over the surroundings. A section by Washburn (1947, Fig. 4) may be taken as an indication of a pressing of the mud material against the surroundings. If there is no counter-pressure it is possible that the fines may be moved a short distance. This hypothesis recalls Hamberg's (1915, p. 604) theory that an expanding debris island may press away surrounding boulders — a theory which was considered speculative by Washburn (1956, p. 841).

Washburn (1950, p. 34 ff., 1956, p. 844) considered cryostatic pressure — i. e. pressure caused by the freezing and expansion of the ground around pockets of unfrozen earth — probably responsible for some sorts of circles. This may be the case also in Sweden but nothing is known for certain about the relations between mud circles and permafrost. The latter is probably a prerequisite for the cryostatic pressure though it may possibly be replaced by a dense bedrock. The distribution of the mud circles, however, favour the cryostatic interpretation. Such violent processes, "soil blisters", as were mentioned by Mullis (1930, p. 65), are, however, not known for certain from Sweden.

It is appropriate to mention also a few other factors that may be relevant. Hopkins and Sigafoos gave a good section through mud circles (1951, p. 76 ff.). They later (1954, p. 57) suggested that a hydrostatic pressure may force deeply situated material upwards. It seems probable that in favourable positions this condition may have some importance for the formation of mud circles, though it cannot be generally relevant.

Steche (1933, p. 231) assumed that colloids in the ground may absorb water in the spring causing the ground to expand. If this theory is on the whole plausible it may have importance for the formation of mud circles — especially as these phenomena belong to vegetation-covered ground. Washburn (1956, p. 846), however, had serious doubts as to the effectiveness of such a process.

Sorted nets

Sorted nets in the sense of Washburn (1956, p. 830) is "patterned ground whose mesh is intermediate between that of a sorted circle and a sorted polygon and has a sorted appearance commonly due to a border of stones surrounding finer material". From what was said above (p. 19) it follows that it is not possible to discriminate between sorted circles, nets and polygons in the Swedish literature. It is evident that proper sorted nets occur. Their vertical and horizontal distribution does not differ from that of the circles (p. 20).

The formation of sorted nets is probably closely related to that of the circles and polygons (p. 20 and 37). If the phenomena are isolated they are described as circles. If the circles are numerous and closely situated they form a network — sorted nets. If they are very closely situated and interact upon each other, which may be especially the case when the pattern is old, they will mutually destroy the circular pattern. Polygons are thus formed. This is the only type of sorted nets known from Sweden.

Nonsorted nets

There are several types of nonsorted nets known in Sweden. The most simple instance is merely a concentration of mud circles. If these occur closely together but without intersecting each other a nonsorted net is formed. The conditions necessary for this formation are the same as those described on pp. 26—29. The regional distribution is still less known than that of the circles. The nets, however, seem to be rare, but there is a very good example on Mt Kyrkstensskaftet, N of Vålådalen, Jämtland.

J. Frödin (1918, p. 28) described another type of nonsorted net. Frödin considered this type a transition between mud circles and nonsorted steps. From his Fig. 8 it is seen that the circles are distinctly convex with deep cracks or furrows between them. One gets the impression that they are also a transition type to nonsorted polygons.

Frödin observed this pattern in the Abisko region (between Abisko and Tjuonavagge). It seems to be a very uncommon type though I have seen similar phenomena in the northernmost Caledonides. The further distribution is not known but I have an impression that the type belongs to the high levels.

K. Nilsson has reported another type of nonsorted nets from the neighbourhood of Mt Ammarfjället, NE of Tärna. This type consists of vegetation-covered hummocks, up to 1 meter high and a few meters in diameter. They are separated by furrows with bare soil, and are therefore clearly visible on air photographs. On the photographs it is seen that the mesh is rather irregular. I have, however, no personal aquaintance of these phenomena and their exact nature as well as distribution is unknown.

The most common type of nonsorted nets is the earth hummock — which is a direct translation from the Swedish term "jordtuva", used also by Washburn (1956, p. 830) and others. Washburn (loc. cit.) erroneously interpreted the term "pals" as "more or less synonymous". Palses have nothing in common, neither genetically nor morphologically (p. 70) — though it is true that in special cases an earth hummock may develop into a pals.

Earth hummocks (Fig. 13) are knobs, very similar to peat hummocks of bogs. Their height may be a few dm but seldom exceeds 1 meter. Their width is also a few dm. The thick vegetation with even cloudberries and other plants is that of the bogs, which contributes to the general impression of peat tussocks. A digging, however, will expose an interior of mineral soil though the peat or humus layer can be thick. Thus there seems to be a gradual transition between earth and peat hummocks.

The interior mineral soil is mostly fine-sandy and so are the interspaces between the hummocks. The latter condition shows that the hummocks have no erosional origin as in other, similar instances (see Ritchie, 1953).

Regionally the earth hummocks are distributed over the whole Caledonian range. In the north they seem to be more sparse. They are especially common

Fig. 13. Earth hummocks with a vegetation rich in lichens, Mt Gellvernokko, northern Jämtland. — Photo by J. Lundqvist 1958.

where the ground is rich in fines, e. g. in the phyllite region of northern Jämtland.

As G. Lundqvist (1944) pointed out the earth hummocks belong to level ground, with rich vegetation and low boulder content. He reported that on gentle slopes they grade into distorted hummocks, oriented along the slope contours. This type, however, is very seldom observed. Another rare transition form on sloping ground are possibly the stripe hummocks described on p. 58. The rareness of these sloping types indicates that the earth hummocks require a rather flat ground.

The vertical distribution of earth hummocks is rather distinct (Fig. 14). They rarely occur below the timber line, probably because the thicker vegetation prevents their formation (cf., however, p. 82). Only in the extreme north are they observed at lower levels — the vegetation here is often more scanty.

The upper limit is as distinct as the lower. It rises from about 800 meters in the north to almost 1200 meters in the south. The limit is thus situated 200—300 meters above the timber line, and follows its rise southwards. This circumstance indicates that the earth hummocks are strongly dependent on the vegetation. At a higher level with lower and more sparse vegetation they cannot form — if on

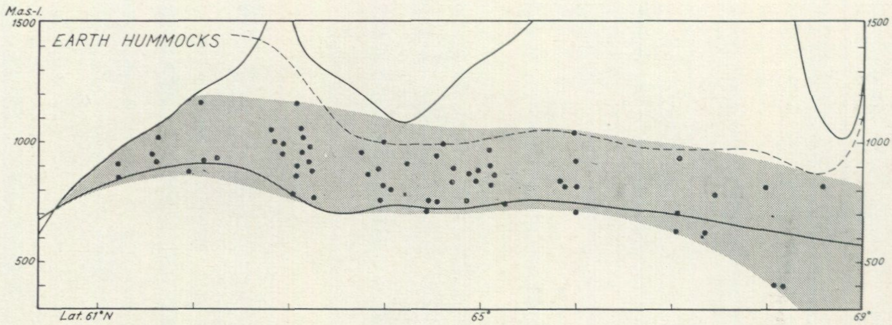

Fig. 14. Vertical distribution of earth hummocks in the Caledonides. For further explanation see Fig. 8.

the whole similar formations can arise they will soon be destroyed by erosion. It is noteworthy that Holmsen (1956, p. 42) stated that the earth hummocks mainly occur above the level 1100 m.

A first tentative explanation of the formation of earth hummocks (which probably at least to some extent correspond to his knob polygons) was presented by Bergström (1912). The cause was supposed to be, as in the case of nonsorted circles, a differential water absorption.

Beskow (1930, p. 628) presented a more exact interpretation which is still accepted — evidently also by Washburn (1956) : The origin of earth hummocks is local unevenness of the ground and vegetation. A thicker vegetation protects the soil from the frost — the surroundings thus are first frozen. The frost in the ground penetrates under the unfrozen parts, thus pressing soil material upwards. If repeated the process will result in a hummock. Its growth will stop when it is high enough to allow the frost to penetrate from the sides. Beskow reported that this interpretation is supported by the inner structure of the earth hummocks.

The interpretation is supported also by Hopkins' and Sigafoos' (1954, p. 58) observation that the living rootlets of the plants go straight downwards. The dead, older rootlets are twisted by the frost heaving. These authors, however, also ascribe importance to hydrostatic pressure in the formation of tussocks. This forces material from deeper layers upwards. Washburn (1956, p. 857) considered this process to have only local importance. His opinion is supported by the Swedish observations.

Sorted polygons

Among the types of patterned ground that are most obvious and have attracted most interest are the sorted polygons. They are referred to as stone rings in Swedish literature. Such phenomena were first observed in Sweden by Svenonius (1880, p. 87). They are later often mentioned in the literature, mostly in rather

Fig. 15. Large stone polygons on Mt Långfjället, northern Dalarna.—From G. Lundqvist (1949, Fig. 3). Photo by G. Lundqvist 1949.

general terms without further description of the localities. A scrutiny of the reports will show, however, that in many cases the phenomena belong more to the classes sorted nets or circles. As the distinction between these types is rather ill-defined it is not always possible to tell the exact nature of a described phenomenon. Therefore the following discussion of origin and distribution to some extent refers to all these three types.

Sorted polygons in the true sense seem to be best known from the southernmost part of the Caledonides. From this region (northern Dalarna) they are described particularly by G. Lundqvist (1949, 1951). The polygons here are often rather large, with a diameter of more than 5 m (Fig. 15). Their pattern is clearly polygonal, hexagons being dominant. Pentagons are also very common. The boulders in the borders of the polygons may be large — ½—1 m. The larger the polygons, the larger are the boulders. According to Jansson (1957) the largest boulders occur in the central part of the borders; towards the finer earth in the polygon centres the boulders are smaller. In spite of the well developed pattern the sorting is not so pronounced. Boulders occur even within the polygon centres and the till material there does not differ from the ordinary till of the surroundings. The centres are slightly higher than the stone borders. On sloping ground the strictly polygonal pattern often grades into a distorted pattern. The polygons become more elongate and on steeper slopes they may even grade into sorted stripes (p. 56).

G. Lundqvist (1949, 1951) studied the orientation of the boulder material in the polygons (Fig. 16). He found that in the stone borders the boulder orientation strictly follows the borders. In the interior of the polygons the boulders are directed towards the neighbouring side. Sometimes they are influenced by two sides. The orientation thus recalls the orientation in the steps (p. 50) and clearly shows that there is (or was) a centrifugal movement within the polygons.

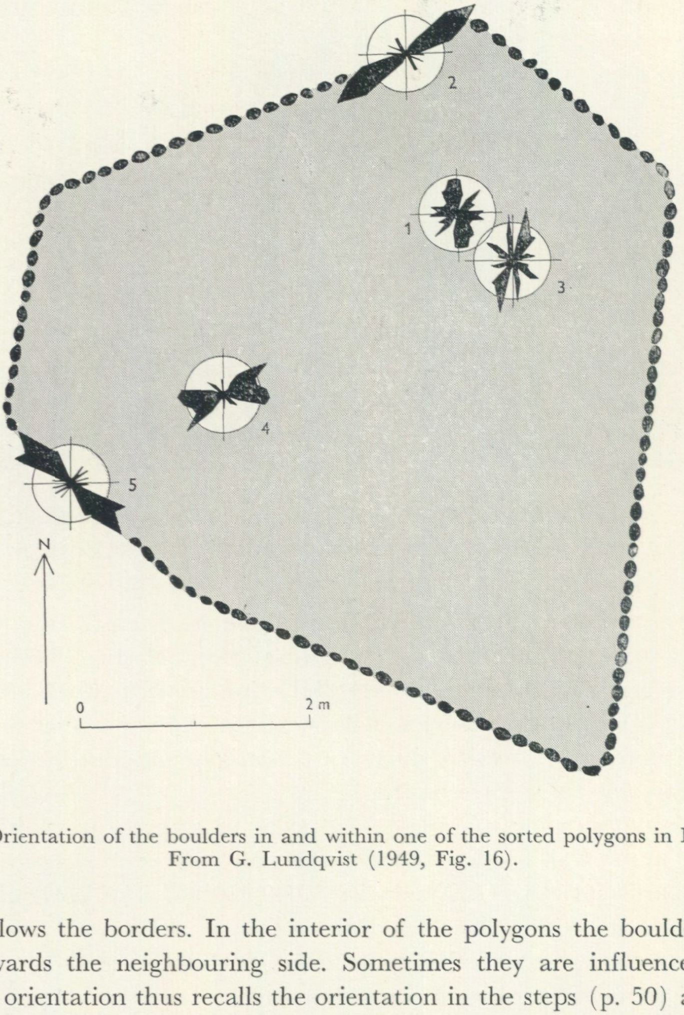

Fig. 16. Orientation of the boulders in and within one of the sorted polygons in Fig. 15. — From G. Lundqvist (1949, Fig. 16).

In the same region Jansson (1957) studied the distribution of the polygons. She was of the opinion that these patterns have fossil features, which is indicated by well-developed podsol formation within the polygons. They also occur on lower levels than the climatic conditions would permit according to her. The vertical distribution according to G. Lundqvist's and Jansson's observations includes the whole space between the timber line and at least the lower mountain peaks, i. e. between 850 and 1 050 meters above sea-level.

Further northwards the exact distribution of sorted polygons is less known. They were reported by most authors, who studied patterned ground in the Caledonides. It is, however, not always clear if the phenomena should be classed as polygons, nets or circles. Nevertheless polygons proper do occur, evidently within the whole range. Only from the northernmost part is certain information about polygons lacking.

However, north of Dalarna the very large, flat polygons seem to be more sparse, at least they are not so common as in the south. The polygons are mostly smaller, perhaps two or three meters in diameter. Often they have more convex centres (see e. g. Beskow 1930, Fig. 11). The conditions described may depend on lack of exact information but there might also be other reasons. The large southern polygons are probably fossil, as was mentioned above but there is no known evidence to indicate that they are fossil also in the north. Thus they may have formed under different climatic conditions.

Another reason could be the present climate. The southern area is one of the regions with most pronounced locally continental climate in Sweden (cf. Ångström, 1953, Fig. 5). The winter temperature is rather low. In the regions further northwards the mean winter temperature is higher or, as in the extreme north where it is still lower, the climate is more maritime. These conditions may have some influence upon the type of patterned ground though it is not quite clear in what manner. Thorarinsson's (1951, 1953) observations may be relevant in this connection. He found that the large, deep polygons belong to the high inland areas, the smaller, shallow types occur on the coast.

The vertical distribution in the north is not exactly known either. As a whole, however, the polygons seem to be scattered over the whole region above the timber line, where soil is available. The observations support Beskow's (1930, p. 636) opinion that the conditions necessary are only a stony ground, sensitive to frost action, and a noncoherent vegetation cover. Of course also a climate where freezing occurs is necessary but this condition is fulfilled throughout Sweden. According to Beskow a high water table and rapid changes between freezing and thaw will accelerate the formation of sorted polygons.

In studies of too limited areas one can easily get a false impression of a vertical limitation of the distribution of different patterns. In some regions it may be found that polygon patterns are restricted to high levels, e. g. between 1 000 and 1 200 meters above sea-level. On lower levels they are replaced by other features. From the Norwegian Caledonides (Jotunheimen, Lat 61°—62° N), for instance, Ule (1914, 1922) reported a lower limit of the patterned ground (mostly sorted polygonal or circular types) at about 1 400 m. These facts, however, may depend on edaphic factors rather than on climatic. A distinct lower limit does not seem to exist. This is shown by the presence of the azonal polygons (in the sense of Troll, 1944) and also by occurrences of polygons of the "mountain type" on rather low levels, even below the timber line, in favourable positions. From the Abisko region Blüthgen (1942, p. 4) reported polygons, stripes etc. down to the upper part of the birch belt. At Mt Stensjöfjället, northern Jämtland, good polygons are observed as low as about 600 m, that is well below timber line.

It must be admitted, however, that we have hardly any determinations of the age of the polygons. It is possible that in many instances occurrences from quite different epochs are compared. Large displacements of the timber line are known (see Smith 1911, G. Lundqvist 1959, and others). Thus there may have been corresponding variations in a possible "polygon zone". The azonal occurrences, however, contradict it.

The upper limit of sorted polygons (Fig. 17) seems to be determined simply by the lack of soil on the highest levels (cf. p. 62). If soil is available they occur even in close connection with the present glaciers. Sjögren (1909, p. 45) reported stone polygons from Mt All. Välivare, SE of Abisko as high as 1544 meters and on Mt Helags, Härjedalen, sorted polygons occur at 1350 meters above sea-level.

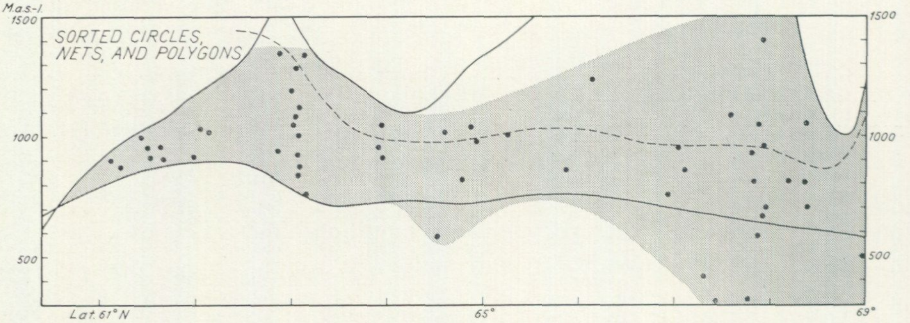

Fig. 17. Vertical distribution of sorted polygons, circles, and nets. For further explanation see Fig. 8.

According to Beskow (1930) and G. Lundqvist (1944, 1949) the sorted polygons belong to a level ground with high boulder content. The vegetation should be poor or lacking. As mentioned above the polygons become more elongated on sloping ground, and thus grade into sorted stripes.

The main Swedish contributions to the explanation of sorted polygons are those of B. Högbom (1914) and Hamberg (1915). They were briefly presented already on pp. 5—6. Both theories imply an expansion during freezing of parts of the ground that are rich in fines. In this process stones and boulders are pushed radially outwards from centres. The theories differ as to the behaviour of the material during thaw. According to Högbom the fine particles adhere to each other when they are pulled back, but the stones are left behind. Hamberg considered the collapsing of finer material around the stones an important process, that prevents the stones returning to their earlier positions. It is probable that both processes are relevant. Direct observations by Vilborg (1955) indicate that the collapsing process is a reality. He, however, was of the opinion that the collapsing occurs when the boulders are lifted upwards with an expanding surface layer at the time of freezing.

The theories mentioned imply that the boulders at the surface in some way or other move radially from certain centres towards the stony borders of the polygons in formation. This movement is well established through G. Lundqvist's (1949, 1951) studies of the boulder orientation. The same observations also indicate that the movement is stopped at the polygon borders — the boulders are here turned perpendicular to the movement. Rydquist (1960), however, studied (extrazonal) polygons on the Isle of Öland with the aid of lichens on the stones within the polygons. He arrived at the conclusion (p. 67 ff.) that the stones make an eternal circulation that is, that at some depth they return from the borders to the centres. Possibly this movement is a reality. In such a case the concentration of boulders in the borders must be explained through an enrichment due to a retardation of the movement when the boulders move towards denser surroundings offering greater resistance.

Sections through sorted polygons, e. g. those of Ahlmann (1936, p. 10), clearly indicate that there is a motion of the material also in the depth. However, this must not necessarily always be the case. Stones may probably also move in the surface, only, towards cooling centres and the like. Thorarinsson's (1951, p. 147, 1953) observations may have some importance also in this connection. As Poser (1931, p. 218) and others, he discriminated between shallow ("floating"), and deep ("anchored") polygons and a transition type. The shallow type belongs to low levels, while the deep type occurs on higher levels. Thorarinsson (1953, p. 37) has "the impression that nowadays only floating polygons are formed on these low level areas, and that the big, anchored polygons in these areas are mainly "fossil" remnants from late glacial time, when the climate was colder than now". These conditions are of interest also in connection with the distribution of the different types of polygons in Sweden (pp. 33—36).

Thorarinsson's observations apparently support Troll's (1944) opinion that permafrost is required for the formation of the large sorted polygons. If these are formed above a permafrost substratum there may be a centripetal movement on top of the permafrost, counterbalancing the centrifugal surface movement. Thus there will be a sorting also in the depth. According to Troll (1944, p. 592) the permafrost table may be replaced by a flat-lying bedrock. The small polygons, on the contrary, should be formed by a simple surface movement. In this connection, however, it must be emphasized that the importance of the permafrost is probably much overestimated (cf. Black, 1952 a, p. 126 ff.).

The aforementioned theories concern the sorting of the originally more homogeneous ground. The sorting may be accelerated also by other factors. Evidently De Geer (1904) also ascribed some importance to pushing in the proper sense of the stones when fine-rich centres freeze. Also Hamberg (1915, p. 604) realized this fact.

Another relevant fact may be the erosion of water in the stony, lower polygon borders. Ahlmann (1936, p. 11) emphasized that the draining occurs in the borders and that fines in that way may be carried away. Already De Geer (1904) ascribed great importance to such an erosion. Probably the erosive effect is responsible for an acceleration of the polygon formation in keeping the border channels free from fines and vegetation, thus making them serve as "cooling centres", towards which stones are moved during freezing. However, this fact can have local importance, only. Often the polygons occur on quite flat ground, even on the bottom of flat basins. In such positions no erosion can occur — which is also demonstrated by the fact that stagnant water is sometimes observed in the stone borders.

The conditions described can well account for the sorting of the polygons but they do not explain the polygonal pattern itself. Nor do they explain the primary origin of the polygons. The pattern is certainly dependent on this origin. Probably there are only two ways to explain the pattern: Either it is caused by an original pattern of fissures of some kind or merely by the fact that the original centres of stone circulation are numerous and rather closely situated. In the latter case a polygonal pattern will probably develop for entirely geometrical reasons, the hexagon being the geometrical figure, most resembling a circle, that can form a pattern without interspaces.

There are several different ways to account for the original formation of embryonal polygons. One possibility is that the stones move towards fissures in the ground, which act as cooling centres. Such fissures may originate through contraction by freezing or drying. These possibilities, which were also accepted by Washburn (1956), are further described on p. 44. It is not impossible that a sorting in a polygonal fissure pattern may result in sorted polygons but the explanation appears less probable. Drying-cracks are usually much smaller than even the smallest polygons and are also seldom well developed in an unsorted, stony till ground.

Then contraction by lowering of the temperature is more probable. This may result in a polygonal fissure pattern (cf. p. 44). Such an explanation would fit well with Williams' (1959, p. 13) opinion that sorted polygons are formed when the ground is permanently frozen, as in periods with a relatively cold climate. However, such a pattern will mostly be tetragonal, which is shown by the non-sorted polygons. The ground cracks in the same way as pure ice (cf. Zumberge and Wilson 1953). It is true that sorted tetragons occur but the majority of the sorted polygons have more sides. This explanation is therefore probably not generally valid, at least.

The theories of Högbom and Hamberg more or less presuppose inhomogeneities in the ground, that is places where the earth is richer in fines than elsewhere. These concentrations of fines attract more moisture than the rest of the ground during freezing. They will therefore serve as centres from where the boulders are moved radially. The theory of "natural inhomogeneities" fits well with direct observations. Troll (1944, p. 586) described the corresponding phenomenon in a smaller scale, namely the formation of miniature polygons by needle-ice. Corte (1959, also 1960) experimentally studied the formation of sorted patterns in gravel overlying a melting ice surface. He found that the pattern is formed by movements on miniature slopes, resulting from a differential melting due to random inhomogeneities in the thickness of the soil cover. In the experiments (Corte, 1959, p. 13), however, the whole process was one of thawing and not of freezing. Nevertheless the results demonstrate an important principle.

A process connected with the thawing that may have some effect on the formation of sorted polygons is the collapsing, mentioned also on p. 45. This process will result in circles (p. 81) but if the centres are situated closely enough the circles influence upon each other, thus giving raise to polygons. However, this process has certainly only local importance, if any.

The element of chance is inherent in theories based on irregularities in the vegetation. J. Frödin (1918, p. 21 ff.) emphasized the fact that frost action is strongest where the vegetation cover is thinnest. This is a very important principle that is relevant also for the regional distribution of patterned ground. In this connection, however, it is noteworthy that Frödin (1914, p. 262) did not consider the sorted polygons frost phenomena; he interpreted the patterned ground as a solifluction phenomenon in the proper sense. Notwithstanding Frödin's views it is evident that spots without vegetation will act as centres of pattern formation (cf. p. 24). Such spots may be caused by wind erosion — Williams (1959 a) even considered the wind action as a condition necessary for the formation of some patterns.

Frödin's (1914) opinion that frost is not responsible for the phenomena of patterned ground was based on his temperature measurements in northern Sweden which showed that there is no multigelation during thawing and freezing. However, as Troll (1944, p. 565) pointed out, the controversy over the multigelation theory — between, among others, B. Högbom and J. Frödin (see B. Högbom 1914 a and the following discussion in the same volume) — was rather futile: Obviously great temperature variations with often repeated freezing will have a greater effect than smaller variations and more infrequent freezing. This fact appears rather self-evident and thus a yearly multigelation is not a necessary condition.

A fact which indicates that multigelation is a quite unnecessary assumption is the velocity of polygon formation. Troll (1944, p. 653) reported that sorted polygons were developed in a recently glaciated area as soon as 10 years after the

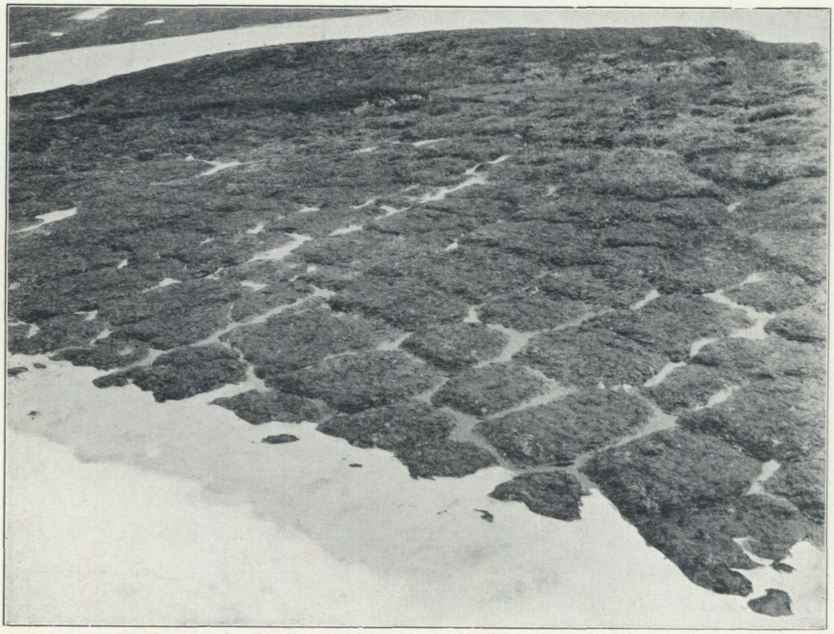

Fig. 18. Nonsorted polygons with a tetragonal pattern. They are flat but distinctly convex. Lake Numirjaure, northern Sweden. — From J. Frödin (1914, Fig. 67).

deglaciation. Corte (1953, p. 41, 1955, p. 95) observed the same rate of polygon formation in the Andes. The reason must be that the movements in the soil are comparatively large, due to the supply of water from below (Beskow 1930, p. 623). Thus it is evident that even with rare freezing of the ground there has been time enough for the formation of sorted polygons since the ice age. A condition necessary is, however, that no vegetation or other processes destroy the embryonal polygons.

Finally it may be mentioned that Washburn (1956) critically examined most theories in the literature, concerning patterned ground. Summarizing his conclusions, he considered the uplift of stones by frost and local irregularities in the ground two factors probably contributive to the formation of some types of sorted patterns. He also considered contraction due to both drying and cooling possible processes in the origin of some polygons. For some reason, however, he seems to consider only drying-cracks as contributive to sorted polygons (cf. p. 45).

Nonsorted polygons

In the following only permanent features are treated. Common mud cracks as well as lichens polygons (Rousseau, 1949, p. 50) and other types also occur but no attention will be paid to such phenomena. This is in consequence with the aim

Fig. 19. Convex nonsorted polygons near Mt Svalaliestjåkko, S of Kvikkjokk. — Photo by V. Lundgren 1934. From "STF:s bildarkiv".

of this paper — to treat the phenomena more or less related to frost action.

Being one of the very few frost phenomena limited to a certain climatic region in Sweden the proper nonsorted polygons (earth fissures, earth polygons) belong to the most interesting types of patterned ground. The typical nonsorted polygons have a tetragonal pattern (Fig. 18). Sometimes polygons with more sides occur, too. The polygons are mostly convex, with lower borders (Fig. 19). Quite flat polygons also occur. Especially in such instances the pattern is visible on the surface only through differences in the thin vegetation.

The nonsorted polygons belong mainly to ground with no boulders. In general they do not seem to be formed if there are boulders. Sometimes, however, scattered boulders occur. Then they are situated in the low borders between the polygons. In this way transitions to sorted polygons are formed. Their centres are in such cases always clearly convex.

It is probable that the fissures between the polygons are sometimes filled with ice. There are no observations of this in the Swedish literature, but according to a personal communication from G. Lundqvist ice fillings occur between polygons on Mt Nuolja, Abisko, even late in the summer.

On sloping ground the nonsorted polygons become more or less distorted. G. Lundqvist (see Fig. 1) considered the miniature terraces (earth waves) as their equivalents on steeper slopes. Morphologically this is right, but it is not clear if

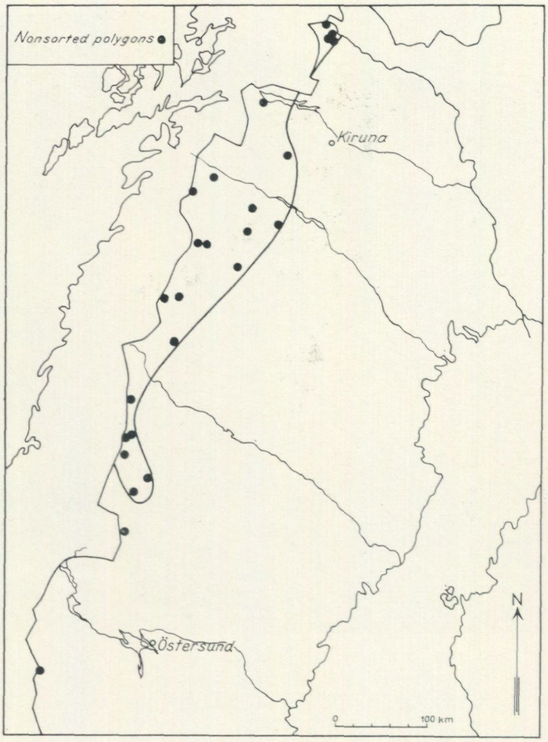

Fig. 20. Observations of nonsorted polygons in Sweden.

these waves are also a genetic equivalent. In any case they are only seldom observed. J. Frödin (1918, p. 17) on the contrary considered some types of stripes the sloping equivalents of the nonsorted polygons. Direct observations of the formation of stripes (Hay 1936) do not support Frödin's views but it is possible that stripes may also be formed through contraction (cf. p. 57 and 89).

Typical nonsorted polygons were described by J. Frödin (1914, Fig. 67; here as Fig. 18) from the Sarek region. Since then they have been reported from other regions too. In general, all observations of such phenomena are made in the northern part of the Caledonides, especially at high altitudes. Thus they have a very distinct horizontal as well as vertical distribution (Figs 20 and 21), a fact which seems mostly to be overlooked in the Swedish literature. G. Lundqvist (1951, p. 81, 1951 b, p. 508), however, pointed out that nonsorted polygons are a more alpine or arctic type.

From Fig. 21 it is seen that there are two exceptions from the general rule of distribution. Both instances are, however, somewhat extraordinary. The northernmost of them, at a level of only 700 meters, is an occurrence in the Remdalen valley, southernmost Lappland. These polygons (observed by G. Lundqvist)

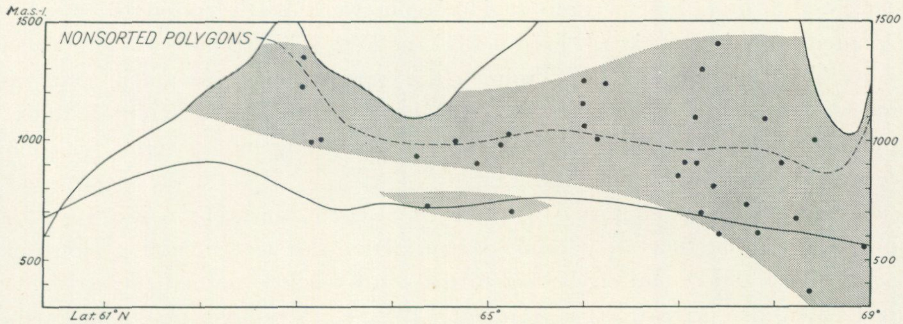

Fig. 21. Vertical distribution of nonsorted polygons in Sweden. For further explanation see Fig. 8.

were situated in fine-grained ice-lake sediments. This is a soil that may possibly be more susceptible to frost action than ordinary till. The southern observation, made by myself, is very well developed polygons at a level of little more than 700 meters at Mt Ahkabene near Gäddede, northern Jämtland. The pattern here was formed in a thin peat, or rather a thick humus layer, though it also came into contact with the till substratum. Notwithstanding these abnormal soil conditions it is noteworthy that this is a region where other types of patterned ground also occur at lower levels than usual — even below the timber line. Thus there might be recent or ancient climatic reasons for the positions. However, a simpler reason may be that this area is comparatively well known through geological investigations carried out in the last few years.

The lowermost observation in the north is of the same type as the occurrence at Mt Ahkabene. This is the observation by Rathjens and v. Wißmann (1929, p. 123) from Pieksennenä in Lake Torneträsk. They described large peat polygons on the shore of the lake (about 343 meters above sea-level) and supposed that the peat polygons were underlain by polygons in the till. Thus even this observation is extraordinary but nevertheless it illustrates the sinking of the zone of nonsorted polygons towards the north.

Concerning the formation of nonsorted polygons there is evidently a consensus of opinion that they originate as contraction fissures. The regular patterns support this opinion (B. Högbom 1914, p. 322) as does the dominant tetragonal pattern. Zumberge and Wilson (1953) have shown that ideal contraction fissures in pure ice form two systems, perpendicular to one another. They also pointed out that the contraction must be rapid — if not, there will be plastic readjustments.

A possible way of formation of a hexagonal pattern was described by Holmes and Colton (1960, p. 13). They reported three cracks radiating from a given point. "With reasonably uniform distribution of such central points, the hexagonal pattern of fractures develops."

The contraction fissures may be formed either by drying or by cooling. In older Swedish literature the nonsorted polygons were mostly considered to have originated as drying-cracks (J. Frödin 1914, p. 259). This opinion was supported also by Ahlmann (1936, p. 19). Probably the explanation is relevant in some instances. Washburn (1956) after his critical examination of different tentative explanations also was of the opinion that mud-cracking may account for some polygons.

The distribution of nonsorted polygons in Sweden, however, mainly supports the hypothesis that they are a result of contraction due to the cooling of frozen ground. They almost entirely belong to the district where permafrost occurs. A closed system like permafrost, as Ahlmann (1936, p. 14) emphasized, is necessary for the formation of cracks. In other cases adjustments of other types will take place. Permafrost is also a condition necessary for the growth of ice-wedges which form the polygon borders. Through one single contraction only thin fissures may be formed in the ground. According to Black (1952 and 1952 a) the coefficient of thermal expansion of frozen ground is almost equal to that of pure ice (51×10^{-6}). Through contractions during one winter only thin fissures may be formed. If the ground thaws in the spring the fissures are closed again. If the frost of the ground persists the fissures, which mark zones of weakness (Leffingwell, 1915, p. 642), will open again on cooling. They are soon filled with snow and ice (cf. J. Frödin, 1914, p. 259), which will keep them open when the ground expands at rising temperature. The adjustments necessary will take place in the soil in the polygon centres. In this way the centres get either a convex (Fig. 19) or a concave (see e. g. Péwé, 1959, Fig. 3) surface, due to the consistency of the soil. This is the original hypothesis of Leffingwell (1915), which is still accepted. According to him the polygons are generally concave, but may be convex on a well-drained ground.

The hypothesis is also supported by direct observations. Black (1951) mentioned that ice-wedges in the fissures contain air bubbles, humus stuff and other material from the sides. Also the original observations by Leffingwell make it evident that the ice-wedges must be formed in many stages. They may be several meters thick and possibly as deep as 10 meters while the maximum width of one year's fissures is 8—10 mm.

Troll (1944, p. 637) considered the ice-wedge polygons belonging entirely to a continental tundra climate. Saying this he had probably in mind the well-known Taimyr polygons (e. g. Troll, 1944, Figs 55 and 56). The distribution in Sweden does not support his opinion as regards the continentality. The district where nonsorted polygons occur is rather maritime — in the more continental area in the southern Swedish Caledonides (cf. Ångström 1953, Fig. 5) they do not seem to occur. On the other hand this type of pattern seems to require a very cold climate. The district in question belongs to the coldest part of Sweden (Ångström, 1953) and here also the "amount of cold" reaching the ground is great (see Fellenius and Rengmark, 1959).

Finally it should be observed that many of the Swedish nonsorted polygons are probably not active. Due to differences in the circulation of water between the borders and centres of the polygons, however, there are differences in the vegetation, which now show the pattern. In the active polygons there is almost no vegetation — possibly due to the presence of permafrost.

As was briefly referred to in the foregoing (p. 41) there is also a type of nonsorted polygons, resembling the sorted type. The exact distribution of this type is not known but they are observed only within the general region of nonsorted polygons. Probably these polygons are formed at least to some extent through a circulation process, similar to that of the sorted polygons.

It is possible that some of the processes that form nonsorted circles (p. 27 and also 81) also can form nonsorted polygons. The condition necessary must then be that there are many, fairly closely situated centres of origin.

Thus fissures, giving rise to polygon pattern can be formed through a collapsing process. However, the contrary too is possible, that is the fissures may be formed at a heaving process, different from the common contraction as well as the collapsing. When the soil underlying a thin, frozen surface layer freezes in the stratified way, described especially by Beskow (1930, 1935 and others), it takes up water from below. This fact together with the volumetric increase caused by the mere freezing makes the soil swell and heave. At least if there are inhomogeneities in the soil — probably also else — the ground will develop a hummocky surface. Around the hummocks fissures will arise by swelling of the underlying beds. This process may sometimes be studied also on roads and railroad banks. If snow or water accumulates in such fissures they may be the origin also of growing ice-wedges and thereby also of nonsorted polygons.

Contraction fissures may possibly also arise when the ground thaws. This hypothesis was first proposed by von Cholnoky (1911, p. 130) and other authors have had similar thoughts. Washburn (1956, p. 852) gave a summary of this and discussed the problem critically. He arrived at the conclusion that the "hypothesis is speculative, although(t) intriguing". Actually, however, it can sometimes be seen in the nature that there is a contraction of the ground on thawing.

On roads and the like there sometimes arise cracks whose total width is not insignificant. On an area about 50 cm wide the cracks can total a few cm. This may be a coincidence but as a matter of fact it approximately corresponds to the decrease in volume at the melting of ice. However, it is rather uncertain if the process has any morphological significance in nature. If so, the conditions necessary are probably a cohesive soil and an immediate evaporation of the water. If the soil becomes saturated with water the cracks will close by flowing. Such a condition may be fulfilled if the thawing occurs by means of insolation rather than increase of temperature. It is also uncertain whether the evaporation can reach such a depth that the process has morphological consequences.

Finally, it is also possible that erosion may sometimes take place in fissures if they are broad enough to be kept open when the ice melts. Such a process was described by Ritchie (1953). Probably, however, the result will be rounded forms rather than polygonal. The process is not known for certain from Sweden.

Sorted steps

The term sorted (and nonsorted) steps was introduced by Washburn (1956). It comprises all those step-like forms, earlier described as stone-banked terraces, soil terraces, soil lobes and the like. The condition necessary is that a higher level is separated from a lower by a marked step, and that this step is downslopes bordered by a stone margin. The step may be at least 2—3 meters high.

The first comprehensive study of such solifluction steps in Sweden was made by Sernander (1905) especially in Mt Hamrafjället, Härjedalen. Since then the related phenomena and problems have been treated by several authors. It is, however, not always clear if the discussions refer to sorted or nonsorted steps. As there is probably no fundamental difference between the two types they will here be treated together as regards their origin and distribution.

Sorted steps are more or less lobate terraces. As Sernander (1905, p. 65) emphasized there is a clear difference between the arctic solifluction steps and Scandinavian ones. The arctic type forms short streams with no distinct distal steeps. The Scandinavian type forms short terraces with steep and distinctly convex distal slopes. However, this is perhaps a too general statement. Even in Scandinavia the terrace pattern may vary according to the slope and moisture conditions. In general the steps become more lobate on steeper slopes. There are not many exact measurements of the slope conditions but Sernander (1905, p. 59) reported that the slopes are often "very steep" but often as gentle as 5°—10°. In general the conditions seem to show the same fundamental variations as were reported from Alaska by Sigafoos and Hopkins (1952): Soil terraces are formed on slopes ranging from 5° to 15°. The corresponding values for lobate terraces are 7° to 20° and for soil lobes 20° to at least 25°.

Probably other conditions influence the terrace form. Factors like increasing slope, which accelerate the soil creep and make it pass into viscous flow will give a more lobate form. Evidently a rich water supply will give this effect too and also the soil composition has some importance.

The Köli schists, which give a fine-grained soil rich in mica, seem to favour the solifluction and consequently also the step formation. This fact was observed also by Svenonius (1904). The conditions in northern Jämtland also demonstrate it clearly: In the area of the Köli schists solifluction is strong and the steps very abundant. In the area of hard Seve schists further eastwards the steps are more sparse (Fig. 22).

Generally there is no sharp limit between terrace-like steps and lobate. It is a common feature that long terrace steps are in detail combinations of numerous narrower and short lobes (Fig. 25).

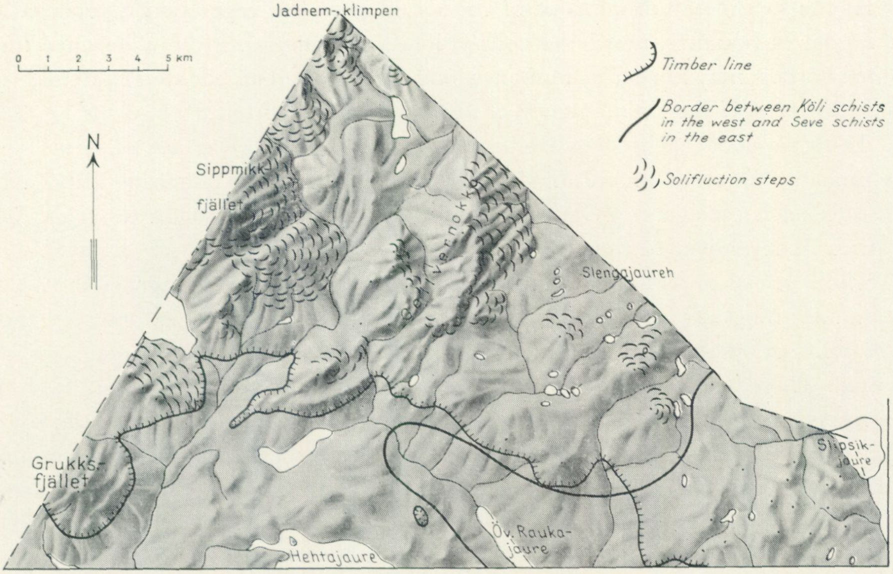

Fig. 22. Sketch map of sorted and nonsorted solifluction steps in the northernmost part of Jämtland. They are located mainly on the eastern side of the heights and within the district of mica-rich Köli schists.

Thus a condition necessary for step formation is a certain degree of slope. On flatter ground there is nothing corresponding to the sorted steps. G. Lundqvist (1944, 1949) considered the stone pits a correspondence but that is only as to the outer conditions, like vegetation and stone content. Sorted steps of course require a certain amount of boulders. According to G. Lundqvist (1944, 1949) and also to some extent according to Beskow (1930), they are limited to slopes with rich vegetation. If vegetation is more sparse the steps are replaced by sorted stripes. To some extent this is true, as the steps mainly occur on vegetation-covered slopes. However, also stripes occur where the vegetation is rich. Probably the difference is mainly a matter of slope and drainage.

It is noteworthy that Holmes and Colton (1960, Fig. 1) are of the opinion that the sorted steps (blockbanked terraces) belong to steeper slopes and wetter ground than the nonsorted steps (solifluction lobes). There is, however, no clear evidence of such a difference in Sweden.

Especially from Sernander's (1905) and J. Frödin's (1918) descriptions it is evident that there is often a rich vegetation on terrace slopes. On the upper surface vegetation is often more sparse. This is probably due to strong wind erosion. B. Högbom (1914, p. 337), however, was of the opinion that these bare surfaces are of the same nature as the polygon centres and nonsorted circles. This explanation may also be relevant, as is indicated by the transitions between polygons and steps, mentioned on p. 49 and 52.

At the foot of the distal slope of the sorted steps the vegetation is replaced by a border of boulders, mostly without visible fine material. From a distance these stone borders may appear as festoons along the slopes. The boulders may hide the general form of the slope, namely a distinctly bulging front.

The stone-foots of the steps are thus characteristic. A special case of sorted steps is probably the stone festoons and stone arcs described by Meinardus (1912). No distinct such types are, however, reported from Sweden, though less clear and rather ill-developed variants are common.

The regional distribution of sorted (and nonsorted) steps comprises the whole mountain range. In all districts where patterned ground has been observed there are solifluction steps. If the ground is rich enough in boulders the steps are sorted. There are some fundamental variations in the regional distribution, however. As was mentioned above the soil is of great importance. Where the soil is fine-grained and consequently has great capillarity, solifluction is more common than on more gravelly ground. From this it follows that in general the step formation is most intense in the Köli schist areas (p. 46), that is, in the western part of the range.

The western distribution of the steps is increased by the precipitation which, on the whole, is greater on the western slopes of the range (see e. g. Wallén, 1953). This statement is valid in general but in detail the steps are often dominantly located on the eastern slopes of particular mountains. This is very clearly seen in northernmost Jämtland (Fig. 22) but in other districts conditions may be different. Sernander (1905, p. 58) reported that he had only registered solifluction steps towards the southern semicircle. Obviously these statements are relevant only in broad outline but they probably demonstrate a fundamental principle namely, the orientation of the steps coincides well with the accumulation of snow drift. It is the same principle that rules the orientation of the glaciers, as pointed out by Enquist (1916). The glaciers and the main snow accumulation occur on the lee side of the predominant precipitation-bearing winds. These are mainly westwinds. Thus precipitation is greatest in the west but the snow accumulation will occur on the eastern sides of the particular heights.

The conditions described indicate an intimate direct relationship between snow accumulation and solifluction. The melting snow will help to saturate the ground with moisture and thus contributes to the soil creep. This opinion is supported also by Sernander's (1905, p. 58) view that solifluction steps above a snow bank, studied by him, were fossil, while below solifluction was still active. The same conditions are indicated by Smith (1920, p. 5) and also Sjögren (1909 a, p. 488) pointed out that the solifluction steps are most abundant below snow fields. B. Högbom (1914, p. 339) and others, however, were of the opinion that all steps are recent.

The vertical distribution of solifluction steps comprises the level below 1 100—1 200 meters above sea-level (Fig. 23). Holmsen (1956, p. 42) mainly emphasized

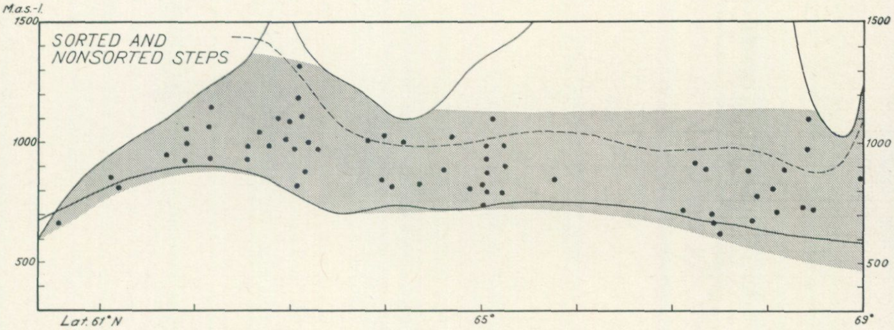

Fig. 23. Vertical distribution of sorted and nonsorted steps in Sweden. For further explanation see Fig. 8.

the high levels — above 1 000—1 100 m west of the southern end of the profile, Fig. 23. The lower limit well follows the timber line. However, from Mt Ransby Gillersberg, northern Värmland, fossil steps with stone banks were described by J. Lundqvist (1958, p. 119, 1958 a, p. 49) at a level of about 640 meters — slightly below the timber line. The steps are rather evenly scattered between the limits mentioned. Only on the highest levels are they more sparse. In the north the observations by B. Högbom (1914, p. 338) from Lake Torneträsk are the only ones on the highest levels with a certain indication of the altitude. The reason for the upper limit of solifluction steps is probably merely the absence of soil. The lack of vegetation is possibly also of importance. As was mentioned above, a certain vegetation cover is necessary, at least for the preservation of the steps. This statement is supported also by Sernander's (1905, p. 65) cited opinion of the difference between Scandinavian and arctic solifluction.

Sjögren (1909, p. 42 ff.) reported a certain difference between solifluction steps on different altitudes at Lake Torneträsk: On low levels the steps form broad terraces, intersected by a polygonal pattern. Higher up, the dominant type is the common steps.

As to the formation of sorted steps there is a consensus of opinion that the step form is a result of solifluction. This is directly demonstrated by the inner structure of the steps. Lobes of the subsoil protrude on and between pockets of the humus layer (see Sigafoos and Hopkins, 1952, p. 179). In a low scarp there is only one such lobe; in larger scarps there may be more. Sandberg (1938, p. 333) in Sweden gave a description of the solifluction steps. He distinguished one central part surrounded by one marginal part and the outermost zone, the front. He found that frost heaving was strongest in the first zone. On thawing material flows out from this zone. The rate of flow he measured as 0.5—12 mm per year. Much more rapid flow occurs, however. Rudberg (1958, p. 115) measured a yearly movement of as much as 15 cm, on a 20 degree slope. The slow movement of the soil is also indicated by the stone orientation. G. Lundqvist (1949, p. 340 ff.)

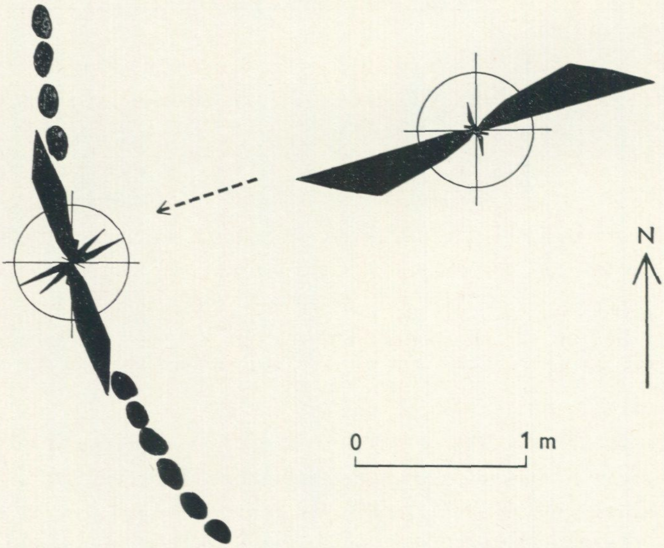

Fig. 24. Orientation of the boulders in a sorted step (stone banked flow earth cone) at Mt Långfjället, northern Dalarna. — From G. Lundqvist (1949, Fig. 10).

found that the interior stones are directed mainly along the movement. In the boulder front they lie parallel with the front (Fig. 24).

Concerning the origin of the soil creep opinions differ (see B. Högbom, 1914 a, and the following discussion). The cause may be either frost action or pure solifluction through water saturation. This was emphasized by Beskow (1930, p. 634) and Troll (1947, p. 166). Washburn (1947, p. 95 ff.) discussed the different theories of solifluction and arrived at the conclusion that the essential of solifluction in permafrost regions is thawing of the frozen ground from the surface. The permafrost table holds up the moisture, causing soaking of the ground. This may result in a gravity-controlled viscous flow. As Washburn emphasized, however, permafrost is not a necessary condition. Seasonal freezing will have a similar effect.

The supersaturation of the soil by moisture is important in this connection. Beskow (1930, p. 625) emphasized that the flow takes place in layers. Therefore the rate of flow is greatest at the surface. This fact accounts for the bulging front of the steps (see also Sigafoos and Hopkins, 1952, p. 183) and is a difference between soil creep and mudflow. In the latter the whole mass moves rapidly with the same velocity (Beskow, 1930, p. 637).

The direct relationship between the distribution of the solifluction steps and the snow drift, as was mentioned above, clearly indicates that the soil creep may be caused also by a mere soaking, without frost action. This was the opinion of J.

Frödin (1914, p. 235 ff.). Thus frost is not entirely necessary though in general both factors cooperate.

The complexity of the step formation, indicated by the aforementioned observations is well established by Williams' (1957) direct measurements and calculations of the processes in the ground. An important fact established by him (p. 52) is that "ice layer-melting does not represent a water increase which can by itself cause flow" — an opinion that differs somewhat from older theories.

The conditions described here do not explain the sorting of the sorted steps. This is a problem that evidently has not been much discussed. Probably sorting is due to the fact that a boulder in a slowly creeping soil will move with greater velocity than the fines (B. Högbom, 1926, p. 260). This fact is often demonstrated in the Caledonides by boulders on slopes with a low bank on the downslope side and a furrow on its upper side.

Another possibility that may be relevant in certain instances, is the outfreezing of boulders through the same process that forms boulder depressions (p. 76), stone pits (p. 24) and the like. This however, presupposes a more or less stagnant solifluction, otherwise the sorting would soon be spoiled. The process is possible in fossil steps and might therefore be an indication of an old pattern. This is no rule, however, as the formation of sorted or nonsorted steps is probably a matter of boulder content, for the most part.

Finally a noteworthy observation by Sernander (1905, p. 54) may be mentioned. He described the not uncommon phenomenon that solifluction steps are broken into two parts. This occurs when the distal part of a step moves considerably faster than the rest of it. The phenomenon is best developed where there is a sudden increase in slope.

Nonsorted steps

As was mentioned above, the foregoing discussion of distribution and formation refers also to the most common type of nonsorted steps (Fig. 25). The only difference is the presence or absence of a stone margin. As was stated in the foregoing this difference is probably mainly dependent on differences in the general character of the ground.

Especially in the case of nonsorted steps it may happen that their interior becomes supersaturated with water. Thus the material breaks through the front and slides away as a mudflow. There are combinations between steps (resulting from slow soil creep) and mudflow (formed by rapid viscous flow). An example of such a phenomenon at Mts Sylarna, Jämtland, was described by Åkerlund (1934, p. 166).

Special nonsorted steps are probably those described by B. Högbom (1914, p. 333) and J. Frödin (1918, p. 28) from Mt Nuolja, Abisko. They described them as terraces with a length reaching 40—50 meters and a width of 1.8—2.7

Fig. 25. Low, nonsorted solifluction step with lobate forms, Mt Sippmikkfjället, northern Jämtland. — Photo by J. Lundqvist 1958.

m. The height of the steps was no more than 5—15 cm but the upper part of each terrace was 30—35 cm higher than the lower. Their remarkable feature was their direction at an angle of 45° to the slope. Such terraces, which may be called "inclined nonsorted steps", are not known from other places in Sweden. Rather similar phenomena, however, occur on Mt N. Kyrkstensskaftet, N of Vålådalen, Jämtland. The genesis of the inclined steps is not clear, but Högbom and Frödin seem to favour an interpretation of the pattern as elongate polygons. Possibly it may be a form of bedrock control, but Frödin (1918, p. 30) considered this explanation less probable.

As most probable, however, I consider an interpretation similar to that of the mud circles. The inclined steps are rather similar to the inclined mud terraces, described on p. 25. Therefore the inclined steps could be very elongated mud circles. This interpretation, however, does not explain the regularity of the phenomenon.

Other steps, which may be classed as either nonsorted or sorted steps, occur in areas with extremely high boulder content. They are formed by masses of pure boulder material, which glide down steep slopes. The pattern will be steps of the same size and shape as the soil terraces, but consisting of boulders and stones without fines. Such "boulder steps" occur among others in Mt Munsfjället and Mts Oldfjällen, Jämtland, and were also described from Sarek by Hamberg (1910, p. 746).

Obviously the boulders cannot glide by themselves. Either they must glide on a substratum of fines or, if they just roll downwards, they will form a common talus field. The terrace form therefore indicates a finer substratum, a sorting. Thus these steps ought to be classed as sorted steps. However, they do not agree with Washburn's (1956, p. 833) definition of sorted steps: "Sorted steps are patterned ground with a steplike form and a sorted appearance due to a downslope border of stones embanking an area of finer material upslope." Considering the step-formation proper, this pattern is nonsorted: No sorting (normally) takes place during flowage. Thus these steps are best considered a transition type.

Sorted stripes

Sorted stripes are often mentioned in the Swedish literature, mostly under terms such as stone stripes, stone streams, striped ground and the like. The most common sorted stripes are channels filled with stones and running down the

Fig. 26. Typical sorted stripe of rather big boulders, and situated on the timber line, Mt Granfjällsstöten, Dalarna. — Photo by J. Lundqvist 1946.

steepest available slope (Fig. 26). The stripe width varies but rarely exceeds one meter. The intervening stripes of finer material are broader. Sometimes the striped pattern is regular with almost equal distances between the stripes. This, however, is not a rule. The regularity seems to be somewhat overestimated in the literature.

Mostly the stripes are simple but they may also be branched. G. Lundqvist (1949, p. 339) mentions a type "composed of two block fronts close to each other." This type according to Lundqvist's Fig. 8 seems to be a transition to sorted steps.

The orientation of the boulders in the stripes is directed strictly down the slopes, parallel to the stripes themselves. This is clearly seen in nature and is also illustrated by Figs 27 and 28 A.

Naturally enough there are transitions between the stripes and common talus fields. The latter may often be striped in their upper part but generally the difference is clear. Talus fields are formed by the slumping of material loosened

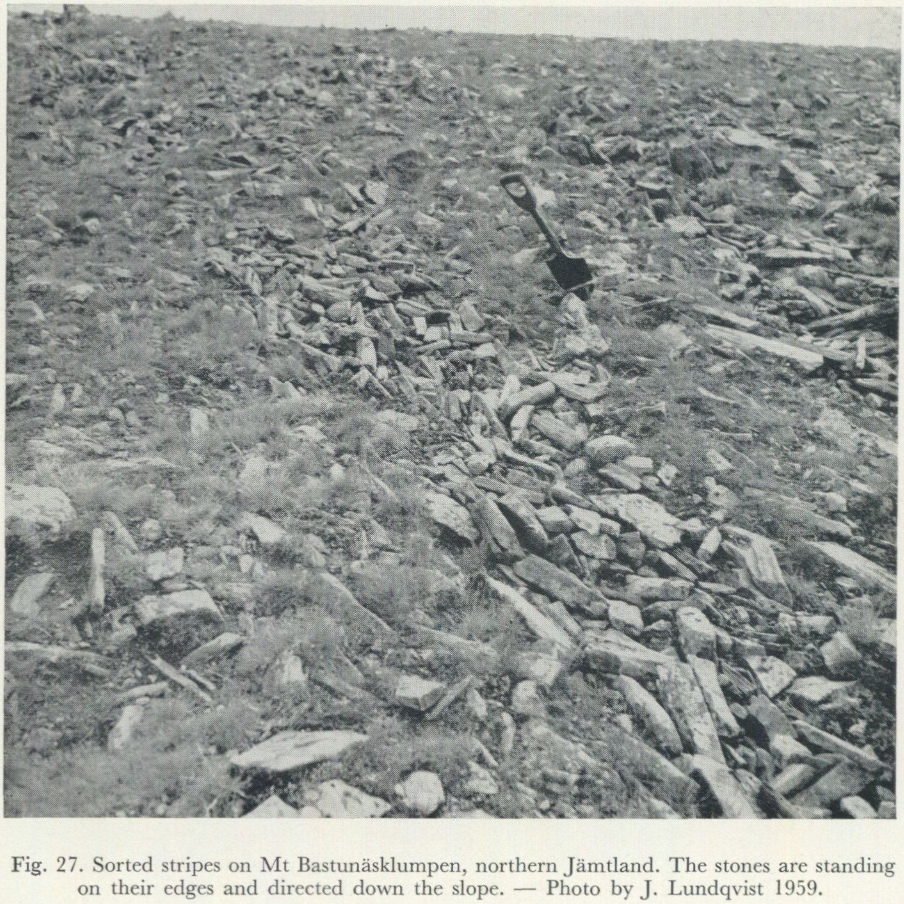

Fig. 27. Sorted stripes on Mt Bastunäsklumpen, northern Jämtland. The stones are standing on their edges and directed down the slope. — Photo by J. Lundqvist 1959.

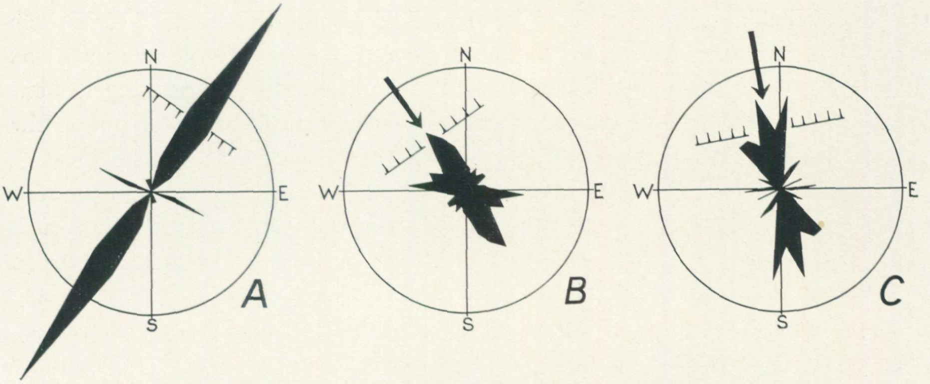

Fig. 28. Orientation of the boulders in sorted stripes from Mt Nuolja, Abisko (A) and from Mt Tidnopakte, N of Lake Torneträsk (B), and in a talus cone from Zermatt, Switzerland (C). The arrows and ornamented lines show the direction of slope.

higher up. The stripe boulders on the contrary do not appear to be slumped, even if there is probably a distinct, slow movement down the slope.

In cross-section the stripes are generally furrow-shaped. In the furrows the material consists of boulders without fines. The boulders are not only directed along the stripes, they are also set up on the edge. In the common type of stripes the boulders are rather flat and sharp-edged due to the schist material and therefore the orientation is very distinctly seen. There are, however, also stripes of more rounded boulders. This type is the "boulder trench" described by G. Lundqvist (1959 a, p. 110, Fig. 66) from the Ultevis and Kebnekaise regions. Whole slopes may be covered with such stripes — G. Lundqvist used the field name "zebra mountains". The boulder trenches are somewhat flatter, and also deeper, than the common stripes.

Another, less common type of sorted stripe is one raised above the surroundings as banks. In other respects they are quite similar to the common type. These raised stripes are not specially described but Beskow's (1930) Fig. 6 seems to illustrate the type. Personally I have seen the raised type on Mt Tidnopakte, N of Lake Torneträsk, and on Mt Blierektjakk, northern Jämtland. As Fig. 28 B shows the orientation along the stripe is less distinct in this type, probably due to some solifluction also down the sides of the stripe.

All types of sorted stripes belong to rather steep slopes — in general steeper than the slopes with steps. Surprisingly enough Holmes and Colton (1960, Fig 1) reported them as belonging to more gentle slopes. There are somewhat different observations of the slope gradients between which the stripes are formed (see Washburn, 1956, p. 836) but in general the limits are 3°—30°. According to Beskow (1930, Tab. I) and G. Lundqvist (1949, Fig. 1) stripes occur mainly on slopes with poor vegetation. They also require a ground with high boulder content.

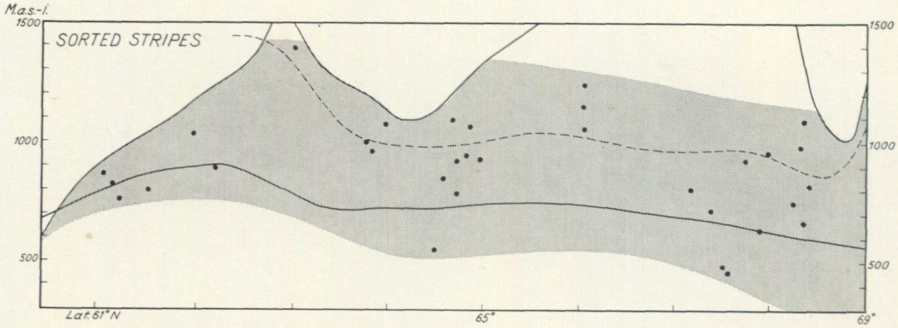

Fig. 29. Vertical distribution of sorted stripes in Sweden. For further explanation see Fig. 8.

The regional distribution of sorted stripes covers the whole Caledonian range with no appreciable variations. About the vertical distribution there has been a consensus of opinion that they mainly occur at higher levels. B. Högbom (1914, p. 335) thus reported a distribution mainly in the region of perennial snow fields. His examples are all from levels above 1 000 meters. A closer scrutiny, however, shows that there are no distinct vertical limits (Fig. 29). Sorted stripes occur on the highest levels with soil available, but also on very low levels, even below timber line. In Dalarna they are observed around the timber line on some of the low mountains, e. g. Mt Granfjällsstöten. In northernmost Sweden they occur even far east of the mountain range itself, on the lower mountains hardly reaching the timber line. Good examples are Mt Kivivaara at Parakka and Mt Palolaki, both S of Vittangi, with sorted stripes on a level of less than 500 meters. Also in the region in northern Jämtland where other patterns occur at abnormally low levels (pp. 36 and 43) there are sorted stripes as low as 500 meters or just above.

Thus there seem to be no climatic limits to the sorted stripes. It is true that all stripes need not be of the same age — some of them might be older, from a time with colder climate. Washburn (1956, p. 837), however, was of the opinion that the stripes rarely are preserved in fossil form.

As to the origin of sorted stripes most authors consider them sloping equivalents of sorted polygons (B. Högbom, 1914, p. 332, Beskow 1930, Tab. I and others). The process studied by Hay (1936) supports that view, as do the common transitions between stripes and polygons. The formation of sorted polygons was treated on p. 36. In the case of stripes it is only to be added that there is also a downslope movement, controlled by gravity. From such an explanation it follows that the stripes require a certain distance before they get their typical shape, as was also shown by Hay (1936, p. 48). The hypothesis implies an upward movement of the fines and a sideward motion of the boulders. It is noteworthy that Salomon (1929, p. 14) considered rillwork from melting snow sufficient for the formation of some striped patterns. He found no signs of downward motion by solifluction.

The initiation of stripes, according to the hypothesis mentioned above, is due to random inhomogeneities in the ground. However, there are features indicating that in some instances other explanations may be applicable. The raised stripes indicate that there is in these instances an upward motion of the boulders also. The sorting in the stripes supports this, the largest boulders being those at the surface whilst downwards the material gradually becomes finer (cf. Poser, 1931, Fig. 2). These facts make it probable that a simple upfreezing of boulders along a line perpendicular to the contours may be of the same effect. Such a line may be caused by rillwork, a hypothesis considered applicable by Washburn (1956, p. 858) in some but not all instances. The hypothesis has some support in the irregular pattern of stripes in places. The process described above would give a rather regular pattern. Another possible origin may be straight cracks of the same type as described on p. 60. As the latter are rare, this explanation is probably seldom applicable.

The raised stripes might be explained also as "solifluction remnants". If the fines between normal stripes slide downwards, leaving the boulders behind, the result would be the same. However, there are no signs observed of such solifluction.

Finally there may be another origin of sorted stripes. As was stated above the common stripes require a certain distance of formation. However, there are also stripes that originate in sloping boulder fields. It is clearly visible that the boulders of the field adjacent to the beginning of the stripes are oriented towards these beginnings. The orientation gradually passes into that of the stripes. There is no direct evidence but conditions observed seem to indicate that the stripes are formed by "boulder creep" from the fields. Such boulder fields are often bordered downhill by a low bank of fine material formed through the pressure of the boulder mass. If this bank is broken and if the slope is steep enough, the boulders may glide through the gap and further downwards. Generally boulders creep faster downwards than the fines. This is demonstrated by the common phenomenon of boulders with an uphill furrow and a downhill bank (see e. g. B. Högbom, 1926, Fig. 5).

Nonsorted stripes

The type of nonsorted stripe emphasized by Washburn (1956, på 837) has "a nonsorted appearance due to parallel lines of vegetation-covered ground and intervening stripes of relatively bare ground". This type is very rarely observed in Sweden. Such patterns seem to occur, however, in the northernmost part of the Caledonides but are usually not well developed. J. Frödin's (1918) Fig. 4 illustrates such stripes on Mt Karanestjåkko, NE of Sarek.

The general appearance of the nonsorted stripes favours the interpretation that they are sloping equivalents of mud circles. There are no observations which

Fig. 30. Stripe hummocks, Mt Sippmikkfjället, northern Jämtland. — Photo by J. Lundqvist 1958.

support Washburn's (1947, p. 94, 1956, på 837) opinion that they are related to the nonsorted polygons. However, no further investigations have been made in Sweden and as mentioned the occurrences are few.

Another type of nonsorted stripe is the "stripe hummock". Apparently this type has not been much reported, at least in the Swedish literature. A very similar phenomenon was described by Låg and Mork (1959, p. 23) from Norway. The stripe hummocks are rather similar to the earth hummocks (nonsorted nets, p. 30) but are elongated to stripes down the steepest available slope (Fig. 30). Their length may be several meters and the width is the same as the common tussock diameter, that is a few dm. Commonly the tussock stripes lie closely together and are broader than the intervening low stripes.

Because this pattern is not earlier observed in Sweden it is not possible to tell its distribution. It is observed in the Caledonides of Jämtland, only. Mostly it is situated on rather low levels, not high above the timber line. Thus the stripe hummocks occur among others even on the lowest mountains reaching above the timber line east of the proper range. Such mountains are Mt Stakafjället, W of Strömsund, and Mt Storgärdesrun E of Lake Kallsjön. They also occur on corresponding levels (700—800 m) in some mountains N of Gäddede. However, it is probable that if they are looked for thoroughly they would be found within the same levels as the earth hummocks.

Also genetically the stripe hummocks are probably closely related to the earth hummocks. Their general features as well as their common occurrences indicate this. Probably the stripe hummocks are a sloping equivalent of earth hummocks. G. Lundqvist (1944, Fig. 185) mentioned from Dalarna another equivalent namely, hummocks elongated along the contours. This type also is very rare — according to my own experience still more rare than the striped type.

The stripe hummocks often occur also together with nonsorted steps. In some instances, e. g. on Mt Sippmikkfjället, northern Jämtland, they seem to be a transition type between earth hummocks and nonsorted steps. Possibly they are formed when earth hummocks are developed on a slope where strong solifluction occurs.

A similar transition type, formed under these conditions, was illustrated by G. Lundqvist (1944, Fig. 176). These phenomena are, however, much less regular than the stripe hummocks. They are rather common in the lower parts of the Caledonides but their further distribution is unknown.

Sorted cracks

A special feature, that has been mentioned now and then in the literature, is a long and straight fissure filled with boulders (Fig. 31). The type is not included in any classification system, not even Washburn's (1956). The reason

Fig. 31. Sorted crack, Mt Fjätervålen, northern Dalarna. — Photo by G. Lundqvist 1945.

may be that Washburn considered it a special case of other fracture types or that it does not fit with his definition of patterned ground: "more or less symmetrical forms..." (1956, p. 824). Obviously Washburn observed and also described the phenomenon (1947, p. 102, 1950, Pl. 11, Fig. 2). As this type of frost ground is closely related to the patterned ground proper it will be treated here. An appropriate term would be cracks, which was used by Washburn (1947) and has the same meaning as the Swedish "blocksprickor", used by G. Lundqvist (1951, p. 78). In consequence with the classification distinction is made between a sorted and a nonsorted type.

The typical sorted cracks are fairly straight lines, cutting through the ground independently of the slope. Mostly they cut the slopes at an oblique angle. They may also cut through low hillocks and depressions. A good example was shown by Washburn (1950, Pl. 11) where they cut through a series of emerged beaches.

The cracks are approximately 1 meter in width and filled with boulders. According to G. Lundqvist (1951, p. 79) the sorting is the same as in other types of frost ground: The boulder size gradually decreases downwards. Mostly the boulders in the cracks are low situated like those of the sorted polygons. However, raised, dike-like types also occur though rarely. In these instances it is not quite certain if they are real frost phenomena. Other explanations are possible, too. They might simply be moraine ridges.

The sorted cracks are rarely observed in Sweden and therefore their distribution is unknown. They seem to be known mainly from northern Dalarna, perhaps simply because this is an area thoroughly investigated by G. Lundqvist, who is the only person who has hitherto observed them in Sweden. However, I have personally seen isolated cracks in the northernmost Caledonides and in Mts Oviksfjällen, Jämtland. It may be a mere coincidence but actually the sorted cracks seem to belong to the same region as the best developed sorted polygons.

Concerning the formation of sorted cracks the problem is to explain their initiation. As soon as a fracture for some reason or other is formed, the boulders will be enriched in it as in the case of sorted polygons, stone pits and the like (G. Lundqvist, 1951, p. 79). As to the formation of such long and straight fractures nothing is known for certain. The independency of the topography immediately shows that they must be formed by some cracking process and not by rillwork or other erosion. Why such long fractures are formed instead of a polygonal pattern is, however, not clearly understood.

It is hard to realize how such frost cracks can arise in the Swedish Caledonides under present climatic conditions and with the present vegetation cover. This fact supports the opinion that they are fossil phenomena. The close connection with the best developed sorted polygons consequently supports the opinion, mentioned on p. 35, that these polygons are fossil, too.

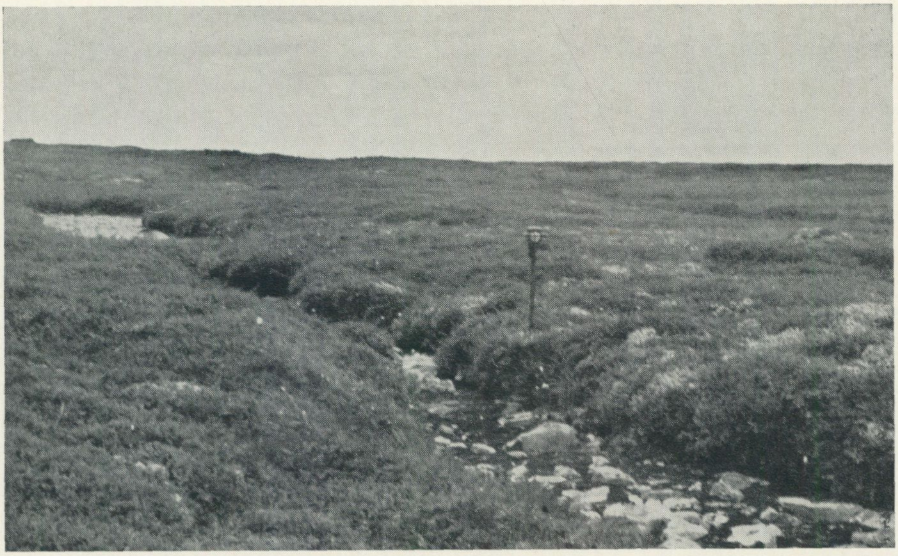

Fig. 32. Nonsorted crack, Mt Vedungsfjället on the boundary between Dalarna and Härjedalen. The furrow may look like a stream channel but does not follow the topography, and ends in both directions blindly. — Photo by J. Lundqvist 1945.

Nonsorted cracks

Fissure lines of exactly the same type as the sorted cracks but without boulders evidently occur in the Arctic regions (see Washburn, 1950, Pl. 12). They are, however, not described in the Swedish literature. Only once I have seen such a feature, namely in Mt Vedungsfjället on the border between Dalarna and Härjedalen (Fig. 32). Also in the mountains N of Mts Sylarna, Jämtland, there are phenomena similar to nonsorted cracks, though not well developed.

Like the sorted cracks this type cuts the slope obliquely. It is similar to small stream channels but ends suddenly and also crosses small depressions. It must be interpreted as a frost crack, in which there was no concentration of stones. If the fossil interpretation is valid, it is peculiar that the crack was not invaded by the surrounding vegetation. The bottom consists of fine soil and would be suitable for plants. Thus this isolated observation contradicts the interpretation of frost cracks as fossil phenomena.

Sorted fields

The fields without characteristic limits are not included in Washburn's classification. As they are certainly frost phenomena and closely related to some other patterns it is appropriate to treat them here.

The sorted fields are simply areas with a pure boulder material in the surface. They form no characteristic pattern but transitions to sorted stripes (G. Lundqvist, 1951, Fig. 74) are common. As the sorted circles and nets are often formed within such fields, transitions to them also occur. A special type of sorted field is the "boulder depression", described by G. Lundqvist (1951 b). Boulder depressions mainly belong to the region below the timber line and are therefore preferably treated below (p. 73). In the higher areas they occur, too, but for some reason or other typical boulder depressions are not common. One reason may be that they are mostly water-filled and therefore observed as ponds with stony bottom.

Thus the sorted fields proper have rather irregular shapes. They may occur on level ground as well as sloping and may cover hills and summits. If the slopes are steep the boulders probably glide downwards with different rates, thus forming transitions to steps and talus fields. Troll (1947, p. 170) reported that the boulder fields may even creep long distances — several kilometers — over rather flat ground.

Especially on sloping ground the sorting seems to consist merely in a boulder enrichment directly upon the fine-grained substratum. If conditions are more stable, however, the sorting is as described by G. Lundqvist (1951 b) : The largest boulders occur on top of the smaller and downwards the material gradually becomes finer.

The regional distribution of sorted fields is not known but they obviously occur all over the Caledonides where the local circumstances are favourable. They especially belong to the higher levels where the frost action is strongest and they can form directly by frost-splintering. This is the region denoted by Tengwall 1920, p. 283) as *"regio alpina sterilis"*. Tengwall (p. 284) mentioned that the lower limit of this region — which is often very sharp — changes markedly from one mountain to another, even to a neighbouring one. He described variations as great as 400 meters on neighbouring tops in the Sarek region. In outline, however, the boulder fields mainly belong to the higher levels. According to Rapp (1960, p. 35) the limit in northern Lappland reaches as low as 1 000—1 200 m. The lowest limit rises southwards and reaches in central Norway 1 400—1 500 m (Holmsen, 1955, p. 12). Recent observations, however, show that even in central Jämtland large areas are covered with boulder fields as low as 1 000 m. This of course occurs only in districts where the general conditions are favourable, e. g. in Mts Oldfjällen and S. Borgafjällen, but it clearly indicates that the local conditions are perhaps even more important than was earlier realized. The general course of the lower limit of the "boulder field zone" is shown on the profiles in this paper.

As to the formation of sorted fields there are two possible hypotheses which seem to be applicable. Either are the boulders enriched from a common till ground or they are formed directly from the bedrock. The last-mentioned explanation was the one mostly emphasized in earlier days (Svenonius, 1909, B. Högbom, 1914, 1926, and others). Högbom (1926) showed that the boulder material is homogeneous and suddenly changes at the limits between different rocks in the underlying bedrock. Good examples of the same phenomenon were demonstrated also by Hamberg (1910, p. 744). Thus the boulders must be formed by frost-splintering of the bedrock itself. Their sharp edges further support this opinion. Högbom (1914, p. 279 ff.) also believed that frost-splintering proceeded even so far as to give fine soil. As a rule such soil occurs in the lower parts of most boulder fields. However, it seems doubtful if any large amount of fine soil may be formed in this way. Nevertheless the close correlation between boulder rocks and bedrock as well as direct observations of boulder fields immediately upon the bedrock give clear evidence that the hypothesis in some instances is relevant.

Especially in the highest mountains where there is no soil the hypothesis must be the only one valid. In such instances transitions between bedrock and boulder fields also are good evidence. Sometimes patterned boulder fields are formed in this way. This is when differences in the bedrock cause a selective frost effect. The arcuate markings, described by Huxley and Odell (1924, p. 216) from Spitsbergen, belong to this type.

The depth to the bedrock and the rich amount of fines in many other instances demonstrate that the boulders are not derived directly from the bedrock. On the contrary the boulders must belong to the till material of the ground. They are lifted up by simple frost heaving and thus a sorting with the largest boulders on top is acheived.

This process was especially studied by G. Lundqvist (Lundqvist and Hjelmqvist, 1937, p. 107 ff., Lundqvist 1951 b, and others). His investigations mainly concerned the lower parts of Sweden and a further account will therefore be given in that connection (p. 74). Also, the process mainly coincides with the one described in connection with the sorted polygons and circles (p. 20 and 36). Here it need only be pointed out that in lower regions the boulder fields almost entirely belong to depressions. In higher levels they evidently form under any topographical conditions, also on slopes and hills.

G. Lundqvist (1951, p. 82) also discussed the age of the boulder fields derived from the bedrock and came to the conclusion that their formation is complex. The boulder fields probably began to form as soon as the area became free of ice. Direct observations, however, clearly show that the process is still going on. In spring and autumn one can hear boulders falling down sloping fields and the entire absence of lichens on scattered boulders also indicates that they must be recently broken away.

Nonsorted fields

This term appears rather unnecessary. However, it may be appropriate to have a term for the unpatterned frost ground also which fits into the classification used here.

The term nonsorted fields thus covers those widespread areas where frost action in the ground occurs but where no structural pattern is developed. The frost action asserts itself merely in an incomplete concentration of stones towards the surface and in a slight solifluction. The latter is demonstrated by the orientation of boulders and stones. In the broken country above the timber line studies of the orientation of the stones will probably show that the orientation generally follows the direction of slope. Thus it deviates from the common orientation of till stones, which is parallel to the ice movement or to some extent perpendicular to it (G. Lundqvist, 1948). The orientation analyses available are, however, few.

Below the timber line amorphous solifluction is also demonstrated by curved tree-trunks in steep slopes. When the soil slowly creeps downwards the trees will have to compensate for this effect in order to grow upwards. The result is the well-known phenomenon of curved birch tree trunks on slopes immediately below the timber line.

The distribution of the phenomena mentioned has not been especially studied but general observations indicate that most of the region above the timber line consists of such ground — except of course where other patterns are formed. The only areas where the ground is not affected by frost action to any appreciable degree are probably especially well-drained regions. Such areas are coarse-grained, hummocky ablation moraines, other coarse-grained and well-drained till ground and deposits of glacifluvial or wave-washed gravel. In many instances these deposits too are probably affected by frost.

Below the timber line information is still more sparse. Probably most of the steep slopes immediately under the timber line are affected by solifluction. There is evidence that this is the case also on lower levels, e. g. on steep valley slopes (G. Lundqvist, 1948, p. 23, Rudberg, 1958). Of course, however, this solifluction must not necessarily be connected with any frost action. As G. Lundqvist (loc. cit.) emphasized the slopes in question must have been strongly water-soaked and susceptible to solifluction immediately after their deglaciation (see, however, p. 67).

Talus

The talus fields may be interpreted as a transition type between sorted and nonsorted fields. They can have a sorted appearance due to a surface of boulders without visible fines. A section through the talus will show, however, that the material is a completely unsorted mixture of boulders and all finer fractions. It may be similar to till but differs from it especially by having more sharply angular stones and a still more unsorted appearance. The outer shape of a talus field may be either a cone or a simple talus slope. The cones occur where the frost splintering takes place on certain limited spots only. If a whole rock-wall is uniformly weathering a talus slope without distinct forms will be the result.

The talus fields do not belong to the patterned ground proper but because they are formed largely by the accumulation of frost-splintered rock debris they may be briefly mentioned here.

In Sweden talus and related phenomena were studied especially by Rapp (1957, 1959, 1960, 1960 a), who classified the types of slope denudation. Most of his types do not belong to the phenomena treated here, but two of them — talus and avalanches — are transition types.

The regional distribution of talus fields to some extent coincides with that of the sorted fields, that is, mainly above 1 000 meters. They are especially located at the steep slopes of our highest mountains where the morphology is alpine. However, in favourable positions talus is formed also on lower levels, for instance where there are steep rock-walls or the bedrock is especially susceptible of frost splintering. Talus fields are not restricted to the area above the timber line. They occur also on much lower levels (see further p. 77).

Concerning talus formation there is probably no doubt of the origin of the debris through frost action. However material derived through erosion by rainfall and rillwork may also collect together with the talus material proper. Thus transition types to alluvial cones and the like may be formed.

The orientation of the talus boulders is not irregular or perpendicular to the slope as would be the case if they were arranged by mere slumping and rolling. Fig. 28 C shows that the boulders — at least in some instances — are parallel with the direction of slope. Thus there is in these instances probably also a sliding in the talus material. These facts were pointed out also by Rapp (1960 a, p. 171 ff., 1960 b, Pl. IX).

The correlation between talus formation and frost action was well demonstrated by Rapp (1960, p. 40—41, 1960 a, p. 106). With the aid of a diagram showing air temperature and annual periodicity of mass-movements he was able to state that: "The diagram gives strong support to the idea that most of the falls are caused by frost-bursting and then released in spring a short time after the air temperature has become consistenty positive..." The same correlation between climate and talus formation is shown by Rapp's (1958, p. 120) scheme, which is a summing up of Fromme's results from the Alps.

Landslides and mudflows

There are many types of landslides and related phenomena (see the classification by Rapp, 1957, p. 179—180, 1960 a) but most of them do not properly belong to the phenomena treated in this paper. From the point of view of patterned ground, related to frost action, there are mainly three pertinent types. The most common are the talus fields, described above. Another type does not morphologically differ very much from solifluction steps, also treated in the foregoing. There seems to be no sharp morphological or genetical distinction between steps, lobes and the like formed by a slow solifluction of saturated ground. The difference is probably mostly a difference in saturation and slope conditions.

A type of mudflow which clearly differs from those mentioned and which may be connected with frost action, is channel-shaped. It forms a rather striking feature in the landscape: Long and narrow (a few meters) channels, running down the steepest available slope. Their bottom as well as their upper end is rounded when they occur in the soil cover — mostly in till. Sometimes they reach the bedrock. If the bottom consists of till it is often striated by the flow.

The furrows are sometimes surrounded by fissures along their edges. The fissures show that new parts of the edges may be loosened and slide down through the channel. In some instances it is also possible to distinguish between more than one generation of sliding. When recently formed the channels have very steep sides, even excavated to a concave profile due to protecting vegetation cover. Later erosion will smooth the forms and old channels probably do not differ from rill-work furrows.

The material derived from the mudflow channels collects at the lower end as more or less fan-shaped accumulations. Sometimes it is quickly eroded away, especially if the mudflow ends at a stream.

It should be observed that this type of mudflow is not exactly the same as that described by Rapp (1960 a, p. 152 ff.) though probably the distinction is not quite sharp.

The "debris drops" (Schutt-tropfen) described by Rathjens and v. Wißmann (1929) and German (1958) from the Torneträsk region are probably a transition type between the aforementioned mudflows and solifluction steps. Personally I have no experience of them, however.

The regional distribution of mudflow channels is unknown. Ängeby (1947, p. 102) described one example from Mt Ullersjöklumpen, northern Jämtland. East of this mountain, on Mt Balter, I have seen a whole series of such channels in similar position, i. e. a steep slope towards the south. Further southwards in Jämtland, at Åre, there is also a series of gullies on the southern slope of Mt Åreskutan. Rudberg (1950) described similar phenomena, though evidently less distinctly channel-shaped, from Mt Kittelfjäll and Lake Ajaure, S—SE of Tärna, Lappland. On the northern slope of Mt Råveåive, at Lake Torneträsk, I have also observed a well developed mudflow channel and also less well developed examples on the northern slope of Mt Äppartjåkko, NW of Kiruna. Thus there seems to be no distinct regional distribution and also no preferred orientation of the phenomenon in question.

The vertical distribution is evidently much more distinct. In almost all cases the mudflow channels occur approximately on the timber line, or not far above or below it. This indicates that the formation of such distinct channels requires a certain amount of vegetation. If the vegetation is too sparse other types of mudflow occur — probably broader types, similar to the slow solifluction. If the vegetation is too thick it protects the ground from such large disturbances.

As to the formation of the mudflows it is clear that they occur when the ground — mostly a rather clayey till — is saturated with water and its limit of stability is exceeded. If this occurs at one certain point the sudden outbreak of the semifluid, watersoaked soil will go on rapidly and form an erosion channel downslopes. Such a point of outburst may be a scar in the vegetation or a steeper part of the slope but the pressure itself may also cause random breaking of the vegetation cover.

The supersaturation of the ground with water may be caused simply by heavy rainfall or snow-melting and probably also, which is of special interest in this connection, by frost action and thawing in the same way as in the case of the patterned ground proper. Thus Rudberg (1950) emphasized that the mudflows described by him occurred after heavy rainfalls. There was no direct connection between the mudflow and the melting of the snow. The same conditions were also emphasized by Rapp in several of his works. Ängeby (1947, p. 102) on the contrary reported that the mudflow at Mt Ullersjöklumpen took place when the thawing of the ground occurred in 1942.

Miniature patterns

Miniature patterns were little observed in Sweden in earlier days. Since Troll (1944) called attention to these structures, however, some observations have been made. As Troll (p. 621) pointed out, at that time no observations of miniatures were known from Scandinavia. Consequently he arrived at the conclusion that the patterned ground here is still more completely dependent on the annual climatic variations than in the Arctic.

However, it is now evident that miniature types occur also. Rapp and Rudberg (1960, p. 149) mentioned that micro-polygons are observed at scattered localities in northern Dalarna, Västerbotten and northern Lappland. These polygons are 0.1—0.2 m in diameter. Fig. 33 shows other small polygons from northern Jämtland.

The micro-polygons are of the same appearance as the large polygons though, of course, they are formed by small stones only. Sometimes the stones seem merely to have collected in fissures in the ground, and thus these polygons are "floating polygons" according to Thorarinsson's (1951) terminology.

Rapp and Rudberg (loc. cit.) reported that the micro-polygons always occur on wind-eroded patches. I would extend that statement and rather say that they occur on bare spots which are not generally covered with water. Mostly such spots are due to wind action but there are other possibilities, too. These are wet patches without vegetation. Wind-eroded patches are often too dry to allow a strong frost effect though it is true that micro-polygons are frequent even in

Fig. 33. Micro-polygons on a moist surface on Mt Murufjället, S of Gäddede, Jämtland. — Photo by J. Lundqvist 1959.

rather dry areas such as the glacifluvial delta at Gröndalen, Jämtland. The condition necessary for the formation of micro-polygons is only the occurrence of a not too dry, naked spot.

The observations are too few to show any distinct distribution of miniature patterns. Those available, however, do not indicate a limitation to any one part of the Caledonides, nor to any particular level.

Another type of micro-pattern that is, however, not so often observed are the micro-stripes. These are sorted stripes of the same magnitude as the micro-polygons, that is their width is some tens of centimeters. Such features are very common on the above-mentioned Gröndalen delta. There the stripes occur on sloping ground in connection with the micro-polygons. It is very clearly seen that the polygons directly pass into stripes as soon as the ground is slightly sloping.

In cross-section the micro-stripes consist of a layer of gravel and fines, less than five centimeters thick and resting upon a humus layer (Fig. 34). The upper surface of this fine-grained material has wave-shaped stripes, directed down the slope. In the furrows pure gravel material is situated. The cross-section is exactly the same as that of the micro-polygons with the exception of the humus layer. The latter clearly shows that the surface material has moved down the slopes on top of the old top-soil layer.

Except for the micro-polygons and micro-stripes, which are sorted patterns, almost no miniature forms are known from Sweden — except of course nonsorted

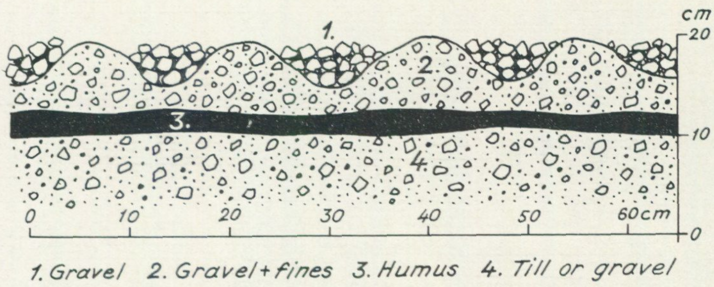

Fig. 34. Section through sorted micro-stripes on the Gröndalen delta, Jämtland. Stripes of pure gravel, and fines with gravel alternate on top of a humus layer. The subsoil consists of a till-like gravel. The scale is approximate, only.

polygons that may probably be caused by mere drying. Fig. 35 shows another exception. This feature is best described as miniature nonsorted steps. It is not clear, however, if these small steps, only some centimeters high and somewhat broader, are a micro-pattern proper or if they should be considered merely a wrinkling as may often be observed on the surface of mudflows and the like.

According to Troll (1944) the miniature patterns are formed through frost cycles of short duration. Thus conditions in the Caledonides ought to be favourable to such a formation to a much larger extent than can be observed. The reason for the sparseness of such observations may be the snow cover, that protects the ground from frost action during a large part of the year. Another reason is probably the stronger annual frost action, that tends to destroy the miniature forms. The small forms are due to the fact that the frost penetrates only

Fig. 35. Small, nonsorted solifluction steps, near Mt Kakats, W of Kiruna. — Photo by J. Lundqvist 1950.

Fig. 36. Palses in the Paltavagge valley, W of Kiruna. They are fissured and eroded, which indicates that they are old.—From G. Lundqvist (1951 a, Fig. 2). Photo by G. Lundqvist 1950.

a few centimeters into the ground (Troll, 1944, p. 562). Thus a frost cycle with deeper penetration will certainly dominate over the shorter cycle.

Notwithstanding the facts mentioned there are probably no fundamental differences between the formation of miniature and large patterns.

The region of sporadic permafrost

This region partly coincides with the Caledonides, as is seen from Fig. 3. Consequently the types of patterned ground here are, to a great extent, those of the Caledonides. Partly the phenomena are the same as in the zone of the boulder depressions, and are thus described together with them. The frost ground, characteristic for the region in question is the palses (Fig. 36).

Palses are hillocks of alternating peat and ice layers occurring on bogs. The width of the palses may vary within wide limits but is seldom less than a few meters. Often the palses are combined to form complexes several hundreds of meters in extent. The greatest height of palses observed in Sweden is 7 meters.

The surface of the palses may be barren peat or it may be covered with a sparse vegetation of lichens and heaths. Especially the barren surfaces are often broken into pieces by drying-cracks, and may sometimes have a "collapsed" appearance. The palses themselves are mostly surrounded by a very wet zone, the "pals lagg" according to G. Lundqvist (1951 a).

The first report on palses in Sweden and on their distribution was given by Fries and Bergström (1910). More recently G. Lundqvist (1951 a, Fig. 10) gave a compilation of all available data on palse occurrences, which is here completed and shown as Fig. 37. He showed that the main area of distribution is the eastern part of the northernmost Caledonides, NE of Lake Torneträsk, and E of that range. Further southwards the palses are much more sparse and mainly occur along the eastern edge of the mountain range. The southernmost palses in the main area of occurrence is in the Sarek region and S of Lake Virihaure. Further southwards there are few observations of palses. K. Nilsson and K. Curry-Lindahl (personal communications) report typical palses from the valleys W and N of Mt Ammarfjället, central Lappland. A still more southerly locality, SE of Mt Helags, Härjedalen, was reported by Smith (1911, p. 529). According to G. Lundqvist (1951 a, p. 225) the area of palses is enclosed by the temperature curve for 120 days with —10° C (see, however, p. 92).

The vertical distribution in the north covers the whole area where bogs occur, i. e. from the boulder field zone of the mountains to the lowest parts of the district, or between 350 and 1 000 meters above sea-level (Fig. 38). The upper limit is the same southwards while the lower limit rises to about 600 meters at Mt Ammarfjället. The isolated southernmost occurrence is situated at about 900 meters.

The formation of palses is initially caused by differences in the snow cover (Hållén, 1913, Fries, 1913, p. 189). Such inhomogeneities may be due to a hummocky bog surface or sometimes to other factors, even human action. In spots with thinner snow cover the frost will reach to a greater depth and the surface will consequently be more raised. As in fine-grained minerogenic soil (Beskow, 1935 and others) the ice in peat ground will be stratified (G. Lundqvist, 1951 a). If the "amount of cold", supplied to the ground in winter exceeds the heat amount in the summer the ice layers will persist. The pals grows and when it becomes higher the frost effect is accelerated.

Fries and Bergström (1910, p. 202, see also Fries, 1913, p. 196) were of the opinion that peat is carried from the surroundings to the pals with the water that collects in the ice layers. This should help to explain the growth of the pals. G. Lundqvist (1951 a, p. 222), however, came to the conclusion that this process does not occur. The only reason for the hummocky form is the excess of ice in the pals peat. This opinion is supported by the fact that there are also palses of minerogenic material. Such palses were reported by G. Lundqvist (1953) and I have also observed other examples in the northernmost part of the Caledonides. However, in Sweden the minerogenic palses do not seem to be very common, though Ruuhijärvi (1960, p. 228) reported that they are

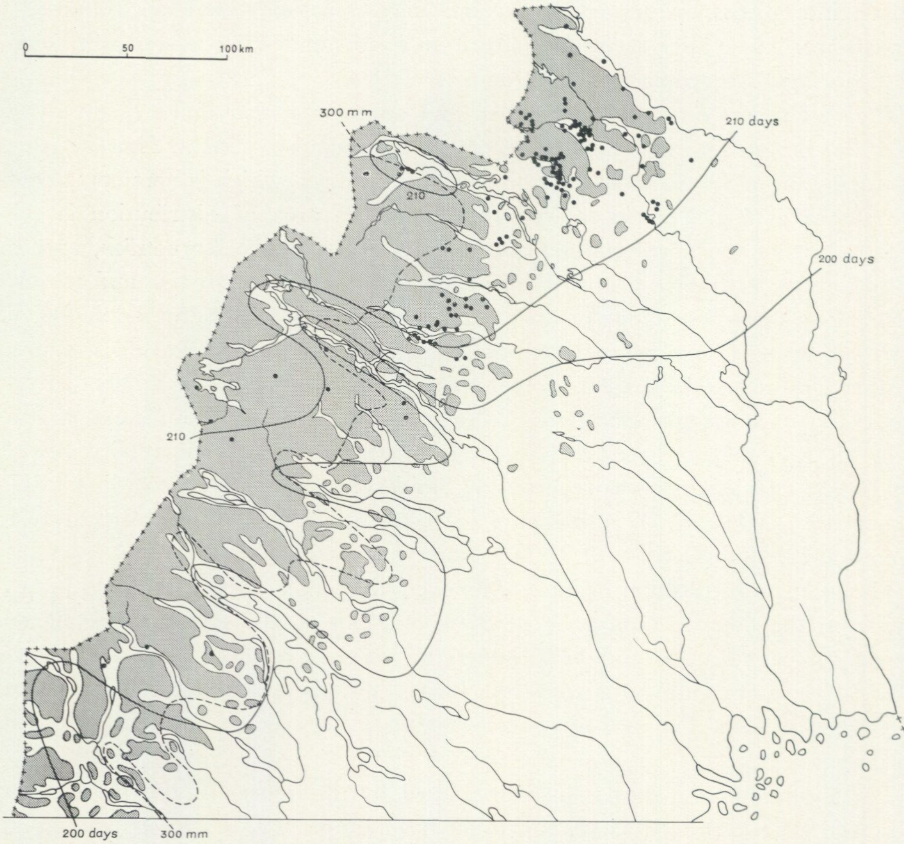

Fig. 37. Observations of palses in northern Sweden. The palses mainly belong to the area with more than 200—210 days with a temperature below zero, and with a precipitation less than 300 mm during November—April. The area above timber line is marked with gray. — Completed after G. Lundqvist (1951 a, Fig. 10).

common in northern Finland. He also accepted G. Lundqvist's explanation of the pals formation.

When more ice is collected in the pals its whole body sinks in the wet bog to some extent and in this way the pals lagg is formed. The shape of the bottom of the palses is unknown but G. Lundqvist (1951 a, p. 215) was of the opinion that it is probably conformable with the upper surface.

The formation of ice layers in the peat, that is, the pals formation proper, is of course a younger process than the peat formation itself. Therefore it is very difficult to determine the age of the palses. Not even pollen diagrams or radiocarbon determinations are of such effect. Through a study of the nature of the peat in combination with pollen analyses, however, G. Lundqvist (1951 a, p. 223) found that the pals studied by him probably began to form somewhat earlier than 1 000 B. C. The formation of palses is favoured by low precipitation, there-

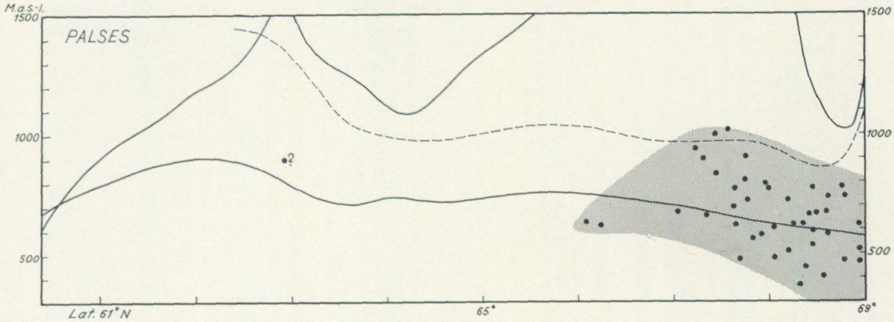

Fig. 38. Vertical distribution of palses in Sweden. For further explanation see Fig. 8.

fore G. Lundqvist (loc. cit.) was of the opinion that the pals formation was most intense before the most maritime periods, that is, immediately before the formation of the recurrence surfaces (cf. p. 92).

It is noteworthy that G. Lundqvist (loc. cit.) also distinguished an end stage of the palses. When a pals is high enough its surface dries, cracks and is eroded by the wind. The deeper the erosion reaches, the more the ice melts and the pals collapses. Thus the often observed pals erosion is a local and not a regional, climatically conditioned phenomenon as one might easily believe from scattered observations (see Sandberg, 1938, p. 337). In consequence with this explanation it is probable that the pals formation still goes on — it is an active frost process.

The forest region

The patterned ground in Sweden outside the Caledonides mainly occurs in the two regions, marked on Fig. 3 as the zone of boulder depressions. Thus it may be appropriate to treat these two regions together, bearing in mind that scattered examples occur even outside this area and that in the future its extension may be found to be somewhat larger. Therefore these two regions and the region without observed patterns, are treated as a unit in the following pages.

Boulder depressions

The phenomena typical for the bipartite region mentioned above are the boulder depressions (translation from the Swedish "blocksänka"). This term was introduced by A. G. Högbom (1905, p. 27) to designate flat, barren fields of pure boulder material, situated in shallow depressions in the landscape (Fig. 39). They occur also above the timber line (p. 62) but are most typical in the forest region. The size of a boulder depression may vary from a couple of meters to large complexes, several hundred meters wide. Actually there are transitions downwards to typical stone pits (p. 21).

Fig. 39. Boulder depression E of the River Guttuån, northern Dalarna. — From G. Lundqvist (1951 b, Fig. 1). Photo by G. Lundqvist 1945.

The first more comprehensive description of boulder depressions was given by G. Lundqvist (in Lundqvist and Hjelmqvist, 1937, p. 107 ff.; see also G. Lundqvist, 1940, p. 67 ff.) and later he also gave a special account (1951 b). Lundqvist found that there is a typical frost-developed stratification in the boulder depressions: The largest boulders are those at the surface; downwards the material is gradually finer. The bottom often consists of a thick, fine-grained soil. This soil can be a clay or other sediment, a clayey till or even humus can act as a cementing agent.

The distribution of the boulder depressions appears from Fig. 40. These phenomena are rather common within the area in question but outside it they are almost entirely absent. The only extrazonal observations are two less typical examples in the Mälar district, published by G. Lundqvist (in Lundegårdh and Lundqvist, 1954, p. 65, 1956, p. 99). Therefore the opinion by Rapp and Rudberg (1960, p. 151) that they are "common all over Sweden, perhaps with the exception of the southernmost province, Skåne" is a slight overstatement.

Boulder depressions are, however, not uniformly distributed within the region. Preferably they occur in areas with high boulder content. Another favourable condition seems to be the presence of a thin cover of fine-grained sediments which makes the soil impermeable. Consequently the boulder depressions are common where there may have been ice-dammed water bodies. In Värmland J.

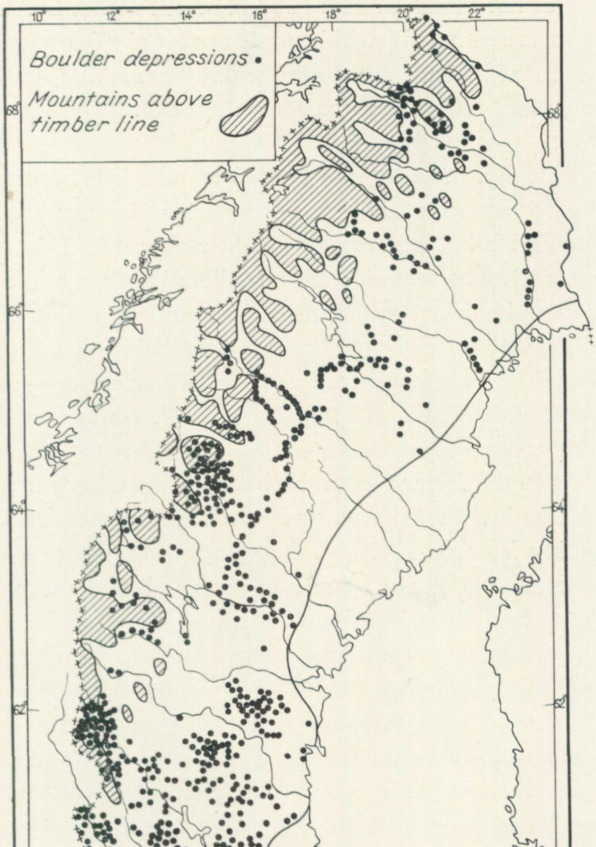

Fig. 40. Observations of boulder depressions in Sweden. The lines encircle the two areas of distribution. — Completed after G. Lundqvist (1951 b, Fig. 3).

Lundqvist (1958, p. 118, 1958 a, p. 49) found that 45 % of the boulder depressions are situated within such areas. 25 % occur below the highest coastline where sediments are more wide-spread. The latter percentage, however, is somewhat misleading, the general area of distribution being the region above that limit.

Actually, however, the conditions mentioned are not the only ones controlling the formation of boulder depressions. In many areas the conditions appear favourable but nevertheless boulder depressions do not occur (see J. Lundqvist, loci cit.). The reason cannot be climatic because in adjacent areas with the same climate boulder depressions can be numerous. Possibly the reason is to be sought in ground water conditions. It is probable that in many instances the boulder depressions are connected with the water table — notwithstanding the presence or absence of an impermeable ground. Actually we do not know much about this aspect of the problem.

As to the formation of the boulder depressions there is probably no doubt that G. Lundqvist's (1951 b and others) interpretation of them as a result of frost sorting is correct. Concerning the age of the process, however, we know very little. The general appearance of the phenomena, with lichen-covered boulders, gives the impression that they are fossil, but there is nothing to contradict a supposition of recent movements. The distribution above the highest coastline, however, also makes it probable that the boulder depressions were early formed — perhaps even periglacially. The distribution does not coincide with that of the common fossil periglacial phenomena (p. 86) and probably the boulder depressions do not presuppose permafrost. However, the resemblance between the area in question and the general course of the present isotherms is obvious (see further p. 97).

Boulder fields

There are some types of boulder fields which cannot be classed as boulder depressions. To these belong the boulder fields described mainly by B. Högbom (1926). Their appearance is quite similar to that of a boulder depression. The boulder material, however, rests directly upon the bedrock and the rock types in the boulders change strictly with those of the substratum. These conditions clearly indicate that the boulders are formed by direct disintegration of the bedrock.

In these boulder fields there is often stagnant water — probably the phenomenon is closely related to the water table.

The distribution of the boulder fields of this type is unknown but outside the Caledonides they seem to belong to northernmost Sweden. Personally I know them only from the area with permafrost and adjacent regions. This is the same region as that of most of the boulder fields described by Högbom. He also, however, mentioned some examples from central Lappland. Such boulder fields may be much more wide-spread — actually of course we do not know the substratum of every single boulder field.

Another type of boulder fields is the "Gråstensmon" (grey-stone heath) SW of Målerås, Småland. This is a hummocky moraine with numerous boulder depressions. The fields consist of rather small boulders, standing on their edges, and they extend even up on to the hills. On the hill sides the stones are oriented parallel with the direction of slope, as in proper frost-affected ground. The whole area strongly recalls the boulder field region in the highest parts of the Caledonides.

G. Lundqvist (1951 b, p. 509) consequently interpreted the phenomenon as a type of frost ground. It is not known, however, why such a phenomenon is developed in this southerly district far down in the forest region. Possibly the till material of easily splintered helleflinta is of some importance.

A similar boulder field was described by G. Lundqvist (1951, p. 80) from the neighbourhood of Falun, Dalarna. This field is situated on a hill slope (Mt Galgberget). The orientation of the boulders indicate that the whole mass is gliding downwards. Even stone stripes are developed and in the lower part there are also elongated sorted polygons. The reason for the good development of this boulder field is partly the presence of silty sediments, partly the vicinity of a factory for sulphuric acid. The smokes from this and from copper factories have killed the vegetation, thus leaving the ground unprotected against frost action (G. Lundqvist, 1951 b, p. 507—508).

Talus

Also in the region outside the Caledonides talus sometimes occurs below steep rock faces. These occurrences are here treated in connection with the region of boulder depressions because their exact distribution is unknown. Evidently, however, they occur also in the area where no other frost phenomena are known. Rapp and Rudberg (1960, p. 151) reported that they occur in all Sweden "from Norrland to Skåne".

G. Lundqvist (1951, p. 81) reported that the talus fields in Dalarna are most common on slopes facing south. In the adjacent province of Värmland J. Lundqvist (1958, p. 119) found that they are oriented in any direction except possibly towards the north. It is uncertain, however, if this is a general principle, but actually it can be observed also in other districts, e. g. eastern Jämtland.

G. Lundqvist (1951, p. 82) mentioned that in many instances talus fields are still being formed. It is probable, however, that in southern Sweden at least they are mainly fossil. To some extent most of the talus fields are probably very old being periglacially formed.

Fig. 41. Large sorted polygons below the mean water level of Lake Storsjön, Jämtland. Near the church of Sunne. — Photo by J. Lundqvist 1959.

Patterned ground on lake shores

The first observations on sorted polygons and the like on lake shores were published by Bergström (1912). He observed such phenomena at several localities in northern Sweden. He mentioned the best developed examples from the region E of Kvikkjokk (Lake Akkaljauratj and Njavve) and from more southerly parts of Lappland (Lake Storuman and others). The phenomena observed by Bergström all belong to the classes sorted polygons, circles or nets. Sometimes the pattern was elongated — at Njavve there were even transitions to solifluction steps.

B. Högbom (1926) observed polygonal patterns in some of his boulder fields. Especially well developed sorted polygons on a shore were described from the Soitola field, W of Vittangi.

In central Sweden, Jämtland, I have seen well developed patterns at scattered localities. The best examples described below occur at Lake Storsjön, around Sunne and on the islands. Another locality of special interest is Lake Kvarnbergsvattnet, N of Gäddede.

At Lake Storsjön (292 m. a. s.-l.) the ground consists of a clayey till. On the flat shores, below the common summer water level, there are sorted polygons at many places. They are very well sorted, with borders of pure boulder material and compact, clayey, boulder-free centres. Sometimes the hexagons are perfectly

Fig. 42. Sorted subcircular pattern below mean water level near the polygons of Fig. 41. Even this small number of boulders was sufficient for the formation of sorted circles. — Photo by J. Lundqvist 1959.

Fig. 43. Stone pits below mean water level, near the patterns of Figs 41 and 42. — Photo by J. Lundqvist 1959.

developed (Fig. 41). Their size may be as large as about 5 meters. In boulder-rich areas there are sorted circles and all transitions between circles, nets and polygons occur. It is noteworthy that even a small concentration of boulders is sufficient for the formation of patterns. Even such irregular types as Fig. 42 shows may be developed isolatedly.

In all these instances the boundary between boulders and clayey till is very sharp and there are not even the slightest signs of erosion, which might have kept them apart. The centres are often strikingly bulging. Thus it seems probable that the pattern formation is still active.

Together with the polygons there are also typical stone pits (Fig. 43). This is very remarkable because vegetation has earlier been considered a prerequisite for stone pits (p. 22). The figure shows that the distinction between boulders and till is as sharp as in the case of the polygons. No gravel has collected on the pit sides and there are no other signs of erosion. The stone pits are irregularly distributed, thus the interpretation of them as the corners of polygons in a surface with low boulder content does not appear probable. The only plausible reason for these stone pits seems to be that boulders are concentrated towards random hollows, where water generally remains.

Concerning the age of the patterns at Lake Storsjön nothing is known for certain. The general appearance of at least the circular patterns clearly indicates that they are recent. If their age were considerable the features would probably have been smoothed. Such pits as are seen on Fig. 43 would certainly have been filled by younger accumulations. The largest hexagons, however, may possibly be older. The surface is here quite flat, the polygons being marked merely by boulder rows.

If these polygons are not recent they have to be very old. G. Frödin (1954, p. 113 ff.) showed that the level of Lake Storsjön was earlier 2—3 meters higher than today. Even if, as Frödin pointed out, the lake lowered its level by erosion at the outlet at a very early stage, the polygons must have been formed during a climate at least as mild as the present.

Another possibility may be mentioned: The size and general appearance of the large polygons recalls the strictly arctic types. Thus these patterns might have been formed during a very cold climate. After the deglaciation and draining of the ice lake, that covered the region, there was certainly no such cold climate. G. Frödin (1954), however, was of the opinion that there was an early draining of the ice lakes before a renewed damming by the Epiglacial ice advance. The fossil patterned ground in Jämtland is discussed below (p. 87) as having possibly originated at the time of this advance. There is a slight possibility that the large polygons were also formed at this stage. Such a hypothesis, however, is mainly speculative and actually appears less probable than an assumption that the phenomena in question are recent.

The locality at Lake Kvarnbergsvattnet (near Junsternäs, N of Gäddede) may

Fig. 44. Circular collapse structure below the mean water level of Lake Kvarnbergsvattnet, Jämtland. Near Junsternäs. — Photo by J. Lundqvist 1960.

give an explanation for the stone pits. In the spring of 1960 there were observed collapsing phenomena (Fig. 44) some 4 meters below the normal present-day water level. The ground (silty till) bulged up at scattered places, evidently due to some type of frost action. The cryostatic explanation (p. 29) seems plausible — irrespective of the complete absence of permafrost or of flat bedrock surface at a shallow depth. Perhaps it is more appropriate to assume a bulging during the thaw or by the absorption of a water excess in concentrations of fines.

Nevertheless bulging occurred. When the bulges thawed out they collapsed, sometimes forming a hollow, a few dm wide. By the bulging a concentric pattern of fissures was formed. In some instances the centre of the bulge was left behind, standing up like a plug, surrounded by a shallow depression and concentric fissures. If such a pattern or part of it can persist until the next freezing it will serve as a cooling centre and affect the upfreezing of stones. This may be a possible explanation of some types of patterned ground though actually no permanent pattern was observed together with the phenomena described.

In this way shallow pools are also formed. They can probably act as cooling centres, responsible for stone pits of the aforementioned type (p. 80). It is also noteworthy that Corte (1955, p. 95) observed the formation of a sorted circular pattern in similar pools.

The regional distribution of "shore patterns" is unknown but if the water conditions allow it they may possibly be formed within the whole region under consideration. This view is supported by G. Lundqvist's (Lundqvist and Hjelmqvist, 1937, p. 110) observation of sorted polygons on the shore of Lake St. Norn, southern Dalarna.

Earth hummocks

Earth hummocks, (p. 30) belonging to the class nonsorted nets, also occur in the forest region. They are of the same type as those of the Caledonides and "show disturbances in soil profiles which the observer spontanously associates with various published pictures of periglacially disturbed layers" (Rudberg, 1958, p. 124).

Their distribution is not exactly known but as Rudberg (loc. cit.) mentioned they occur even near sea level in central Sweden. His observations well agree with those of Sigafoos and Hopkins (1951) from Massachusetts, where the same phenomena occur in a temperate climate.

The earth hummocks are probably recent phenomena. This is demonstrated by the fact that they form in meadows, after cultivation has ceased. Besides, they are easily destroyed and it is unlikely that they would be preserved for a long time after their growth has stopped.

String bogs

Phenomena often considered as a climatic effect, comparable with other types of patterned ground, are the strings of bogs in the subarctic and boreal regions. Because the comparability is somewhat doubtful the description will be made brief and thus it is not possible to quote but a small part of the extensive pertinent literature. A good reference list, however, is that of Drury (1956).

The strings are low ridges on the bogs, separated by wet hollows (Fig. 45). The vegetation of the strings is generally moss *(Sphagna)* and sedge. The hollows can have naked dy surfaces or a vegetation of *Sphagna*. The orientation of strings and hollows is always perpendicular to the direction of slope. Thus on a slope they follow the general contours and on flat-lying, vaulted bogs the pattern may be concentric. On still flatter bog surfaces even polygonal pattern with a mesh of tens of meters may occur. Examples of this are observed in the Kiruna region.

The regional distribution of string bogs is somewhat smaller than the northern area of boulder depressions, as shown in Figs 3 and 40. In Värmland string bogs occur in the northern half of the province (J. Lundqvist, 1958, p. 108) and in Dalarna over most of that province (G. Lundqvist, 1951, p. 98). Along the Bothnian coast string bogs do not occur but otherwise they are common in the whole of North Sweden.

The vertical distribution covers most of the range available but in the outer parts of the region string bogs are mainly located in the highlands. In valleys and plains the bogs are of entirely different types with other vegetation.

The strings were interpreted as frost phenomena by Svenonius (1904). He

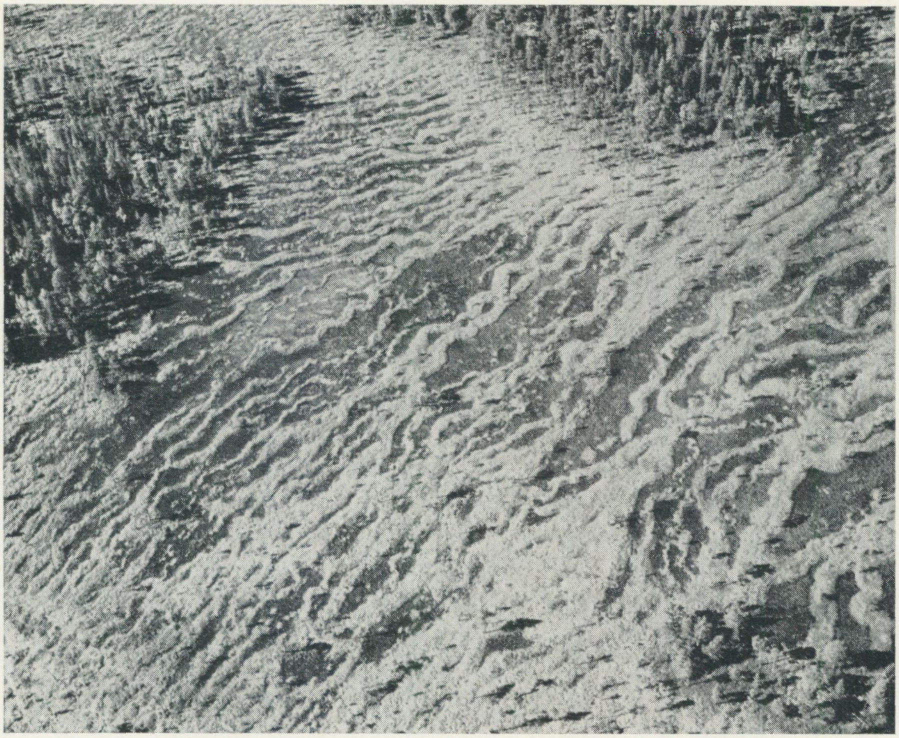

Fig. 45. String bog NE of Strömsund, Jämtland. The strings have a vegetation of sedges and are parallel with the contours. — Photo by J. Lundqvist 1958.
Av Försvarsstaben godkänd för spridning.

explained them as an effect of the movements of water and frozen ground. Later Troll (1944, p. 639 ff.) especially emphasized their climatic significance.

The exact mechanism of the string formation is not well understood. Sometimes the strings are interpreted as solifluction phenomena, comparable with common solifluction steps. This, however, seems improbable when the consistency of the sedge peat, the stratigraphy and other factors are considered. Sjörs (1946, p. 64) also stated that a slow solifluction may be of some effect for the growth of deep hollows but cannot explain the initial formation of strings. Auer (1920, p. 85) emphasized the effect of ice thrusting. As G. Lundqvist (1951, p. 99) pointed out this may account for a widening of hollows but it does not explain the origin.

We therefore have to assume that the formation of strings and hollows is mainly an effect of biological processes as emphasized by Ruuhijärvi (1960, p. 216 ff.) and others. Or rather: it is a combination of biological and hydrological factors (Sjörs, 1946, p. 58 ff.). It is of critical importance, as pointed out by G. Lundqvist, (1951, p. 99) that the *Scirpus caespitosus* tussocks grow in rows. If these rows are perpendicular to the slope they may dam up a water body. This is the initiate of the strings.

Entirely physical origins of the initial string formation were mentioned by Drury (1956, p. 73 ff.): Slight movements in the peat — not comparable with solifluction — can cause a wave-like appearance of the bog surface. A most probable process is that of water running through a loose vegetation cover on a hard (frozen) substratum and then being able to form a festoon-like rib pattern. This can later, through biological processes, develop into the common string pattern.

If embryonal string-and-hollows are formed the frost thrusting may certainly be of some effect. So is probably also the frost effect in the strings. G. Lundqvist (1951, p. 100) observed that there is often ice in the strings even as late as midsummer. He was of the opinion that the same process which accounts for palses and earth hummocks is relevant also in the case of strings. He mentioned that the stratigraphy of the string peat supports this view. Drury (1956, p. 72) on the contrary found no differences in the frost conditions in strings and hollows.

Nonpermanent frost structures

Two processes closely related to the formation of patterned ground may be mentioned. These are needle ice (Sw. pipkrake) and frost boils of the roads. None of them results in a permanent ground pattern and the description will consequently be brief.

Needle ice itself is no pattern but its importance for the formation of some patterns was emphasized, especially by Beskow (1930) and Troll (1944). It is a well-known phenomenon implying that needles of ice are formed under the surface layer of the ground. The needles are oriented perpendicular to the cooling surface and upon them rests the surface material of gravel etc.

Needle ice is an important agent for the formation of miniature patterns. As it occurs repeatedly — especially in spring and autumn when the number of short-lived cold periods is great — there are probably conditions favourable to miniature patterns in the whole region where it occurs — that is the whole of Sweden. Other processes, like rainfall, vegetation and human action, prevent the complete formation of such patterns. The only exception is the miniature patterns in the Caledonides (p. 67). The climatic conditions necessary, however, occur in all Sweden as is indicated also by the rather strong frost activity in all Sweden. It is a well-known phenomenon that the boulders in the fields successively freeze upwards (cf. Rapp and Rudberg, 1960, p. 151, and others). The frost effect is strong enough also to tear off rootlets and thus cause damage to the vegetation (cf. Beskow, 1934).

Frost boils are morphologically related to the nonsorted circles (p. 24). They occur on the roads when water released from thawed out road material is worked into the soil through vibrations caused by the traffic. Then the soil becomes semi-liquid and breaks through the surface layer (Fig. 46).

Fig. 46. Frost boil on a road in Indal, Medelpad. Notice the knife as a scale! — From G. Lundqvist (1959 a, Fig. 50). Photo by Th. Lundqvist 1957.

The frost boil formation was especially studied by Beskow (e. g. 1930 a, 1935). Frost boils mainly occur where the water table is situated close below the surface — that is in moist places, and where the bedrock reaches close to the surface. As far as is known frost boils do not form spontaneously — the traffic vibrations are a prerequisite. Of course the damage is repaired — otherwise the process would probably form nonsorted circles exactly similar to natural ones.

The regional distribution of frost boils seems to comprise all Sweden but the phenomenon is not uniformly spaced. The variations, however, are evidently caused by the soil conditions and road quality and not by climatic factors: Frost boils are preferably located in regions with frost-sensitive soils, that is silty clays, fine-grained till and the like /cf. Hoppe, 1945, p. 32, Friberg, 1951, p. 11 (289)/.

Isles of Öland and Gotland

Conditions on these isles are extraordinary and in some way favourable to the formation of patterned ground. Here the flat-lying bedrock of Ordovician and Silurian limestones and shales is covered with only a thin soil or lacks such a cover altogether. This is the so-called Alvar ground. The vegetation is sparse and patterned ground due to frost action can be formed. This was observed by Hesselman (1915) who described sorted nets and polygons from the Isle of Gotland. Small polygons of the miniature type are the most common features but stone pits and earth hummocks also occur.

The polygon formation was here studied by Hesselman (1915) and also by Rydquist (1960). The latter included among other things the lichens on the stones in his research. He concluded that the stones make a nonstop circulation in the polygons. Thus the polygons are of the deep, rooted, type in spite of their small size.

The reason for the formation of patterned ground on these isles is partly edaphic. They are to be found in the sparse vegetation and in the shallow, flat bedrock. The latter serves as substitute for a permafrost table, as was pointed out by Du Rietz (1925) and Troll (1944, p. 596). It is noteworthy that the climatic conditions are sufficient for polygon formation even though it is comparatively mild on the Baltic isles.

Fossil patterned ground

In the southernmost province, Scania, there occur fossil periglacial phenomena. They are not seen on the surface of the ground but are shown by the stratification. The phenomena include different types of involutions and ice-wedges. The types do not differ from those that are well-known from the periglacial areas in northern Europe and elsewhere, and therefore they probably do not require any further description.

Attention was first called to these phenomena by G. Lundqvist (1951 b, p. 509) who observed descriptions of phenomena that could possibly be interpreted as periglacial in some old map descriptions (Jönsson, 1884, p. 20, De Geer, 1887, p. 59, 1889, p. 31). As G. Johnsson (1956, p. 34) pointed out not all of these phenomena are really of the periglacial type but this does not reduce the value of Lundqvist's observations. Johnsson's work well confirmed Lundqvist's prediction of a zone with periglacial phenomena in Scania. As Johnsson pointed out there are several more observations described in the literature that probably refer to such phenomena (Erdmann, 1881, p. 102, 1881 a, pp. 18, 22, Wennberg, 1949, Figs 39, 40, and others). Later Johnsson (1958) described more localities with ice-wedges and related phenomena, all formed in front of the advancing young Baltic ice stream (cf. also Nørvang, 1942, p. 203). Probably, however, not all of Johnsson's observations really refer to periglacial phenomena. Johnsson (1959) himself seems to have become aware of that and also Möller (1959, p. 40 ff.) proposed other interpretations that might be valid in some cases.

Notwithstanding these critical remarks there is certainly a zone with fossil periglacial phenomena in Scania. The zone possibly extends even north of Scania, in western Småland (Johnsson, 1956, p. 308 ff.) but in general it comprises only those areas that became deglaciated before the mild Alleröd time (about 10 200—8 900 B. C., see e. g. Iversen, 1953, E. Nilsson, 1960, and others), i. e. during the Older Dryas epoch.

On Fig. 3 the zone in question comprises only Scania but, as Johnsson (1956, p. 36) pointed out, it may have extended along the West Coast. The proofs of this are not quite incontrovertible but evidence for instance, lies in the pictures published by Munthe et al. (1923, Figs 42, 48, 49; also in Sandegren and Johansson, 1931, Figs 22, 28, 29) from the Gothenburg region. Thus the zone coincides closely with the periglacial zone deduced by other means by Cailleux (1942, p. 71 ff.). According to Cailleux (p. 47) the periglacial effect after the Older Dryas epoch was limited to a narrow zone along the ice front.

A fact that is probably not so well-known is that there are signs of a former periglacial zone also in central Sweden (Jämtland). On mapping the glacial deposits in this province a large wedge of gravel was observed NE of Laxsjö. The width of this wedge — in till — was about half a meter and the depth at least 2—3 meters. Such a wedge might be formed by other means than frost action but the observation is noteworthy in connection with some other factors.

Professor B. Asklund has called my attention to the fact that two large wedges in gravel occurred at the gravel pit of Pilgrimstad. This gravel, in which mammoth remnants were found, is submorainic and the locality was comprehensively described by Kulling (1945). The ice-wedges were probably exposed for only a short time, as they are not mentioned in Kulling's description. However, they appear in Thorslund's unpublished first report on the mammoth finds to the Geological Survey (dated October 25, 1944).

G. Frödin (1956) also described wind-polished bedrock and stones, which he interpreted as periglacial, from the Anjan region, western Jämtland.

The observations are still too few to allow any wide conclusions but nevertheless they seem to indicate a faint periglacial activity in Jämtland. This activity may be related to the reactivation of the ice-sheet, by G. Frödin (1954) called the Epiglacial ice advance. It is true that this advance is somewhat doubtful but there are also other signs of a reactivation of the ice. Gavelin (1906) observed a Postglacial readvance of the ice in the Caledonides in northern Sweden. Along the Bothnian coast there is a zone with till, consisting of reworked sediments (Kalix till; cf. Fromm, 1949, Hoppe, 1959), which may also indicate a reactivation. There is no evidence of any correlation between these observations but it is noteworthy that at least Frödin's and Fromm's observations may be considered situated at approximately the same distance from the central part of the main ice divide — which was, however, not the last one (cf. J. Lundqvist, 1959, p. 22).

It is of special interest that the Pilgrimstad ice-wedges occurred in submorainic gravel. This gravel according to Frödin was overridden by the Epiglacial ice. Radiocarbon age determination of organic material from this deposit does not support Frödin's view (G. Lundqvist, 1957, p. 7) but these problems are very complicated and far from being solved. Notwithstanding the discrepancy mentioned there might be a similar evolution in Jämtland as in Scania: An ice advance and periglacial action connected with it.

Finally it may be pointed out that Virkkala (1959) identified a zone with periglacial phenomena in southern Finland, N of the Salpausselkä. There is no equivalent to this zone known in Sweden. Phenomena of periglacial character are observed in the corresponding part of Sweden at scattered localities (e. g. J. Lundqvist, 1958, p. 139) but they are perhaps always better explained in other ways. It seems possible that also the phenomena described by Virkkala must not necessarily be a result of frost action.

Table 3. Patterned ground arranged according to mode of formation

Origin / Procedure		Topography	Cracks	Differences in soil	Differences in vegetation and snow cover	Rill-work	Accidental
No mass-movement			N. polygons N. cracks				
Upward movement of	Fines		N. polygons	Debris islands S. nets S. polygons N. circles *N. stripes*	N. circles Earth hummocks S. polygons *Stripe hummocks* *N. stripes* S. nets		Debris islands S. nets S. polygons (N. circles) (Earth hummocks) *(Stripe hummocks)* *(N. stripes)*
	Stones	Boulder depressions	S. polygons *S. stripes* S. cracks	Debris islands S. nets S. polygons *S. stripes* Stone pits	Stone pits	*S. stripes*	S. polygons *S. stripes* *S. steps* (Stone pits)
Downward movement of	Fines	*Mudflow*		*Mudflow*	*Mudflow*		*S. steps* *N. steps* *Mudflow*
	Stones	*Talus*	*S. stripes*	*S. stripes*		*S. stripes*	*S. steps* *N. steps* *S. stripes* (Debris islands)

N. = nonsorted S. = sorted (Less important) *On sloping ground, only*

Summary of the formation of patterned ground

The formation of different types of patterned ground was discussed in the foregoing. This survey in combination with other critical discussions, especially those of Washburn (1956), shows that the following processes are probably responsible for patterned ground in Sweden. The following summary of course does not exclude the possibility that in other regions there may be other processes active.

The pertinent processes are summarized in Table 3. Even if this table might well be used as a classification basis for patterned ground it is not intended to be a new classification. Its purpose is simply to show the main principles ruling the formation of the main types of patterned ground. One must remember that some patterns are probably rather complex phenomena, all aspects of which cannot be shown in a single table. The table is based on two main factors: the initial origin of the pattern, and the process of movements in the ground — neglecting the causes of the movements.

In the table the topography is considered a simple type of origin. Of course topography is a condition necessary for the formation of all patterns in so far as their type is always dependent on the slope conditions — the patterns are not similar on slopes and on flat ground. This fact, however, is indicated by the italicizing of those types that require sloping ground for their development.

The column "topography" has another sense: It includes such facts as the hydrological differences between hillocks and hollows. In the latter the water-table may be situated close to the surface, a fact influencing upon the formation of patterned ground — e. g. of boulder depressions. Furthermore there is the fact that a steep slope allows the products of frost action — congelifracts and the like — to be removed simply by gravity, that is, without the further contribution of frost action or solifluction.

That cracks can serve as the origin of some patterns is a well-known fact. Generally the cracks form a polygonal pattern but also straight fracture lines occur. The fractures are probably most commonly formed by contraction due to cooling. The distribution of certain patterns (p. 44) gives strong support to this hypothesis. However, in some instances other types of contraction may be responsible for the fractures. Contraction cracks due to drying are a very common feature on mud surfaces and other usually moist places. There is a possibility that such fractures can also be the origin of more permanent patterns. The formation of contraction fractures due to thawing was discussed on p. 45. Even though objections can be raised to this hypothesis it is not entirely out of the question that patterns may originate in this way. However, as was pointed out on p. 45, such cracks probably require almost immediate evaporation — that is, they should perhaps better be considered drying-cracks.

Fracture patterns originating in these different ways are preserved by the collection of ice or sediments directly in the open cracks. They can also serve as "cooling centres" towards which stones and other material move on freezing. As was pointed out especially by Beskow in his several works (1930, 1935 and others) ice layers in the ground are parallel to cooling surfaces and the material consequently moves towards such surfaces.

"Differences in soil" includes all such origins that presuppose inhomogeneities in the ground, that is random concentrations of fines or stones. Differences of that kind cause differential absorption of water whether by freezing, by common capillary movements, or otherwise. Similarly, differences in the mode of freezing itself may occur due to the different insulating effect of different materials. Concentrations of stones may thus serve as cooling centres towards which other stones move on freezing.

The last-mentioned effects are very similar to those of differences in vegetation and snow cover. They cause differential cooling and freezing of the ground, resulting in differential water absorption and mass movement. Evidently frost action must be strongest below bare spots in the vegetation cover. Such spots may be caused by the type of vegetation itself, by scars of animals and in many other ways. Differences in vegetation in turn may cause differences in the thickness of snow cover, resulting in stronger frost action in tussocks and other higher spots of the ground.

The rillwork effect is perhaps too special to deserve a special column but evidently rillwork furrows may serve as cooling centres which may probably be of some effect on the formation of stone stripes.

The column "accidental origin" may probably appear rather unnecessary but in it are included pattern types which can form even in the absence of visible inhomogeneities of the aforementioned types. Evidently the frost effect will first be produced at places with especially favourable conditions. If there are no such places the frost effect will of course not fail to operate but will do so at random.

The aforementioned origins are no proper patterns themselves. A patterned ground is produced by the motion of the different constituents of the soil in connection with such initial forms. In the table a distinction is made between patterns produced by the motion of the stones and by the fines. Another distinction is made dependent on the direction of movement, whether upwards or downwards.

The movement upwards is commonly believed to be a result of frost action though other causes are possible, too. The fines are raised on the formation of ice layers and the enrichment of water in the upper soil layers. Apart from the freezing process hydrostatic or cryostatic pressure may be responsible for some raising but they probably do not offer a general explanation. Another possibility is that the fines are raised by the pressure and sinking of adjacent boulders — thus the process is combined with the gravity-controlled downward motion of boulders.

In combination with the aforementioned initial features the raising of fines is responsible for many circular and polygonal patterns. On slopes it may possibly account for some striped patterns. However, it is rather probable that the polygonal patterns especially are complex phenomena in the formation of which more than one of the processes described take part.

The upfreezing of boulders and stones is caused by the formation of ice layers below the stones in the way illustrated by Beskow (1930, Fig. 4) which is the same principle causing the needle ice. It is of principal importance that the stones are prevented from returning to their original position. The effect may be the result of collapsing, by ice pressure and other factors, as described in the foregoing.

In combination with cracks the upfreezing of stones may result in polygonal or striped patterns. If the upfreezing takes place on a broad front it will give boulder fields. The boulder depressions are a special case controlled by the topography and the relation between ground surface and water table. If the upfreezing is not so complete or if there are irregularities in the soil composition, circular or polygonal patterns may arise. Where there are scars in the vegetation, caused by rillwork, wind action etc., the process in question gives concentrations of boulders which are either more or less circular or striped.

The downward motion of material is controlled simply by gravity and the effect is, in general, increased by a large water content. The most simple case is the downward creep of the fines. According to the nature of the creep one discriminates between different types, such as mudflow, solifluction and the like (see Washburn, 1947, p. 85 ff., and references). In this connection attention is paid only to the morphological results and therefore the complicated problems of these types are not treated. Only the type "mudflow" in a special sense (p. 66) is here distinguished from the slower types of solifluction.

Such mudflows are probably common where there are inhomogeneities of different kinds in the ground. In more homogeneous ground — or rather where the inhomogeneities are of no effect — the result of the downward motion of fines are the steps, but also here mudflow may occur.

The downward motion of boulders and stones may be a mere slumping or rolling. Of perhaps greater interest is the gliding down slopes when the soil is saturated with water. In this case it is a sort of soil creep, though the heavy boulders creep faster than the fines.

By slumping the only initial feature necessary is that the slope is steep enough. In this case simple talus accumulations are formed. Through the slow motion striped or stepped patterns arise. The steps are really a transition between types formed by the downward motion of stones and fines, because the whole mass moves together. The boulders, however, sometimes move faster, giving rise to sorted steps.

Because any gravity-controlled motion in these cases needs a slope, all the types mentioned are partly caused by topographical conditions. The only exceptions are the debris islands formed by a pressing up of fines through pressure of the boulders. Probably, however, this interpretation of debris islands is not generally applicable.

Summary of the relation between climate and patterned ground

In a regional investigation of the present compilatory type it is not possible to study the meteorological conditions at each locality though this of course is desirable. The best way is to compare the regional distribution with existing meteorological maps. For this purpose the maps in "Atlas of Sweden" were used.

Under such circumstances the correlation between distribution and meteorology cannot be expected to be complete: The existing curves are probably not exactly those determining the formation of frost phenomena — in many cases intermediate curves or combinations of curves are applicable. Local meteorological conditions also cause ostensible divergences from the rules. For these reasons the comparison between distribution and meteorology is not made quite without pre-suppositions. It is based on the results concerning the formation of patterned ground obtained in the foregoing and what can be deduced to be the main meteorological preconditions.

One must also bear in mind that probably not all patterns are active today and that the distribution is thus not in all details comparable to existing meteorological conditions.

Except for fossil patterned ground, whose distribution was treated in the foregoing, patterned ground may be divided into a few groups with certain differences in distribution. Many of the less common types are too little known to allow the distribution to be determined but probably they also belong to the main groups hereunder. These are: 1) The palses; 2) The nonsorted polygons; 3) "The Caledonide types"; 4) The boulder depressions.

1. The distribution of palses was described on pp. 71—73. It comprises a very distinct area in northernmost Sweden, mainly E of the Caledonides. Further southwards there are scattered localities within that mountain range. The relationships between palses and climate were studied by G. Lundqvist (1951 a). He (p. 225) came to the conclusion that the pals region is determined by the duration of the cold period and corresponds well to a curve for 120 days with —10° C. However, I cannot agree with the latter statement. Lundqvist's general statement that the palses belong to a region with prolonged cold and relatively low (winter) precipitation is, however, certainly correct.

According to my opinion the essential precondition for the formation of palses is simply that the loss of heat in winter is greater than the heat supply in summer. This hypothesis is supported by the maps by Ångström (1953 a, maps 1—4). They show that the palses belong to a region where maximum temperatures are reached during relatively few days — e. g. the area with less than 100 days with +10° C or more coincides well with the main pals region. It is also significant that in this region the summer temperatures are relatively low (Ångström 1953, maps 5—9).

A still better resemblance is shown by Ångström's (1953 a, map 20) curves for the duration of the winter season. The curve for 210 days with a temperature below zero clearly marks the southeastern limit of the pals region. Around the River St. Lule älv there is some discrepancy but this is probably mainly due to generalized drawing of the map: The palses occur in the mountains and small valleys around the large river valley, while the warmer region comprises this large valley itself. In the Kiruna region there is also some discrepancy: Palses are lacking in a region around the River Torne älv, inside the curve in question. Probably the reason here is relatively higher summer temperature than in the surroundings (see Ångström 1953). Even in this region, however, embryonal palses seem to occur far E of the general limit. In the Vittangi region for instance I have seen very large but low string-like peat hummocks with ice in the middle of July on the large bog Ripakaisenvuoma, NE of Vittangi. Also on the bog Kannasvuoma, N of Vittangi, there are large, pals-like peat hummocks.

Also the southernmost pals localities fit rather well with the winter curve. In the region Lake Virihaure—Sarek—Ultevis is a distinct lobe eastwards of the curve where palses occur. In the Tärna region where the most certain southernmost palses occur the curve for 210 days with less than 0° C does not occur but the curve for 200 days makes a broad lobe eastwards exactly over the pals region. Even the southernmost, somewhat doubtful occurrence falls within a region with relatively long winters. However, small discrepancies have certainly no meaning because quite local conditions may favour pals genesis even outside the main region — as was emphasized by G. Lundqvist (1951 a, p. 225).

When referred to the mean annual temperature the palses belong to the region with a temperature between —2° and —3° C (see Östman, Wallén, Ångström, 1953, Pl. 32). The correlation with this isotherm is, however, not so good as with the aforementioned.

The pals region does not comprise the whole area encircled by the curves in question. As G. Lundqvist (1951 a) pointed out a thick snow cover will protect the ground from freezing — therefore a strong winter precipitation will counteract the effect of low temperature. Thus palses are lacking in the west where precipitation is strongest (cf. Wallén 1953). Fig. 37 shows that the northern, main part of the pals region is limited by the "winter curve" in the east and by a curve for approximately less than 50 mm precipitation per winter month (or less than 300 mm during November—April).

The summer precipitation may also be of some importance: Wenner (1947,

p. 205) pointed out that the drying up of the pals surface during a warm and dry summer reduces the heat conductivity of the peat. Thus the ice in the pals is better preserved than under a wet surface layer.

The southern pals occurrences do not fit with the precipitation curve. Probably the reason is, as G. Lundqvist (1951 a, p. 225) pointed out, that palses there occur in locations exposed to the wind, which will account for a locally thinner snow cover.

To some extent, especially in the south, the curves for the thickness of snow cover (Östman, Wallén, Ångström, 1953, map 31:1) are better applicable. The curve for 120 cm marks the limit of the pals region — the palses occurring where the snow cover is thinner than this value.

Thus the regional pals distribution is probably dependent on the duration of the winter season and on the winter precipitation. The vertical distribution is downwards limited by the same factors and upwards simply by the absence of peat bogs on the highest levels.

2. The nonsorted polygons — at least in so far as they are ice-wedge polygons — are probably favoured by low temperatures and also by temperatures around the freezing-point. The low temperatures themselves will cause only thin fractures — the condition necessary for their growth is a repeated freezing, or rather a low temperature at depth together with temporary melting of the snow on the surface. Through the latter process water for filling of the fissures is obtained.

This hypothesis is supported by the distribution. Nonsorted polygons occur in the northern part of the Caledonides. This is not the coldest region in Sweden during the cold season, but in spring and summer the region has the lowest temperatures (Ångström, 1953). The distribution coincides quite well with the area encircled by the isotherm for 0° or +1° C in May. During October—April the temperature here is well below zero, and during June—September well above zero. In the summer period, however, it is relatively low (mean temperature never above +10° C) which favours a preservation of ice-wedges from one winter to another.

The May temperature may be of importance, being low enough to allow contractions. The melting of the snow cover in that season gives a large water supply which percolates into the fissures and refreezes, thus widening the ice-wedges.

Referred to the mean annual temperature (cf. Östman, Wallén, Ångström, 1953) there is probably also a direct relationship between the nonsorted polygons and the coldest region in Sweden. The area of distribution is encircled by the isotherm for about —3° C.

The upper limit of the nonsorted polygons is probably simply due to the lack of soil on high levels. The lower limit, as well as the regional, has climatic causes. It may be mentioned that the lower limit steadily sinks northwards. On

North Cape, northernmost Norway, I have seen nonsorted polygons less than 300 meters above sea-level, and possibly the limit is still lower. The timber line is here situated below the sea-level.

3. The "Caledonide types" is used here as a collective term for all the main patterns, such as circles, nets, polygons, steps, stripes and cracks, whether sorted or nonsorted. The only exceptions are the nonsorted polygons already treated. The term is not quite adequate but is used for brevity's sake, because the main area of regional distribution comprises the whole of the Caledonides.

Of the main types mentioned at least the sorted circles, nets, and polygons, as well as stone pits and earth hummocks occur far outside the Caledonides. The exact distribution is not known due to too few observations but in favourable positions some types occur even in southern Sweden and on the Baltic isles.

In the Caledonides — here in the sense of the region above and around the timber line — the patterns in question may be divided into two groups: The sorted circles, nets and polygons, and the stripes all occur even on high levels. Their upper limit seems to be determined by the limit of soil. The stone pits, earth hummocks and solifluction steps do not ordinarily reach appreciably above 1 000 meters. Of these types the steps also have a distinct lower limit, approximately corresponding to the timber line.

Within this vertical range of distribution the different patterns are evenly spaced. It is true that the timber line variations are great in an east-west direction — they are generally around 100 meters but may be as large as 200 meters (Fig. 4). Thus it could be claimed that the patterns occur on more limited levels relative to the timber line and consequently occur on lower levels in the east (and west) than in the central part of the mountain range. Corte (1953, Graf. 3) described such a variation in the Andes. However, in Scandinavia the variations shown on the profiles exceed the variations of the timber line. Also the field observations indicate that there are no definite regional relationships between the timber line and the pattern types — though of course within limited areas the patterns commonly change from one level to another.

These facts together with the regional distributions support a hypothesis that the patterns are not climatically limited within the Caledonides. The climate probably permits the formation of those patterns in most of Sweden. Already from Troll's (1944, e. g. p. 565) investigations it is evident that no distinct climatic limit of the patterned ground can be expected. The more often freezing is repeated the stronger the mechanical effect. Lower temperatures in general will cause larger and deeper patterns. Therefore the occurrences of patterned ground, most abundant above timber line, will successively become rarer and smaller southwards. The occurrences of patterned ground at favourable locations even in the southern parts of Sweden indicate that its absence in most of Sweden below the timber line is caused by other factors than climate. Probably the cause is found in the presence of richer vegetation with trees and also to some extent in the human activity.

In so far as the patterns depend on the vegetation, which in its turn is climatically controlled, there is of course a direct relationship between patterned ground and climate within the Caledonides. This fact accounts for the sharp lower limit of patterned ground. von Post (1945, p. 38) emphasized the fact that this limit coincides with the upper limit of bog formation. Even if later observations show that this is far from being rule it is expression of the same conditions.

The limitations above the timber line can also be ascribed to edaphic factors rather than climatic. Those patterns that are favoured by or require the presence of vegetation disappear upwards where the coherent vegetation subsides.

There may possibly be a few exceptions from the general rule. As was pointed out on p. 35 the large, well-developed sorted polygons and the cracks seem to be most abundant in the southern part of the Caledonides. This is the most pronounced region with locally continental climate in Sweden (see Ångström, 1953, Fig. 5). In the rest of the range the climate is rather locally maritime and thus there could be a connection between formation of the patterns in question and the continentality of the climate. The observations are too few, however, to allow definite conclusions. Thus another reason could be relatively low winter and autumn temperatures in combination with relatively low precipitation in the area in question (Ångström, 1953, Wallén, 1953).

Another exception could be the solifluction steps, sorted and nonsorted. They are distinctly located between the timber line and the upper limit of coherent vegetation cover. This limitation could be an effect of edaphic factors but also of the precipitation. The precipitation over the whole year is by far the largest in the Caledonides. According to such a hypothesis the steps are the result of a mere saturation of the soil with water instead of frost action. The hypothesis is supported by the distribution shown on Fig. 22 and also by Sernander's (1905) observations. It is most probable, however, that both frost and precipitation have some effect.

4. The distribution of the boulder depressions was shown on Fig. 40. The discussion of the relations to the climate is complicated by the fact that we do not know for certain if the conditions are still favourable to their formation or if they are entirely fossil. Some features in the distribution may be relevant, however.

The area of distribution appears to be limited by the highest coast-line (see G. Lundqvist and E. Nilsson, 1959). This could easily be taken as a proof of the boulder depressions being old — originating from a time when a large part of Sweden was still submerged by water. However, as was pointed out by G. Lundqvist (1951, p. 507), this is not the case as to the details. Boulder depressions also occur below the highest coast-line (cf. p. 76). The relative sparseness there may depend on the fact that favourable ground occupies much smaller areas here: The till is often wave-washed or covered with fine sediments.

A probably more important fact is the close resemblance between the limit of boulder depressions and the isotherms (Ångström, 1953). This is valid for most parts of the year and it is therefore no point in claiming any special isotherm as relevant. If, however, it is assumed that the condition necessary is as low a temperature as possible it would be natural to use the isotherms for February. Among these the isotherm for —5° C coincides with the limit of the northern area of boulder depressions. In the south the resemblance is not so good, but the isotherm for —3° or —4° C is the one that correlates best.

Terminology

For the benefit of Swedish geologists, working with patterned ground, translations into Swedish of the English terms used in this paper are given here. As far as possible these Swedish terms agree with the ones used in previous works, especially those of G. Lundqvist. In some instances, however, new terms are introduced. In other cases the sense of the terms as presented here differs to some extent from that used previously. This concerns especially the term "stenring", which was earlier used in a very wide sense. For this reason it is here changed to "blockring". Concerning the terminology of landslides, mudflows and similar phenomena reference is made to the works of Rapp.

Sorted circles = blockringar
Debris islands = jordöar
Stone pits = stengropar
Nonsorted circles = jordringar
Mud circles = jordringar s. str.
Mud terraces = jordterrasser
Sorted net = blocknät
Nonsorted net = jordnät
Earth hummocks = jordtuvor
Sorted polygons = blockrutor
Nonsorted polygons = jordrutor
Sorted steps = flytvalkar med blockfront
Nonsorted steps = flytvalkar
Inclined nonsorted steps = sneda flytvalkar
Sorted stripes = stenströmmar
Boulder trenches = blockdiken
Nonsorted stripes = jordränder
Stripe hummocks = jordvalkar
Sorted crack = blockspricka
Nonsorted crack = jordspricka
Sorted field = blockfält
Nonsorted field = strukturlös frostmark
Pals = pals
Boulder depression = blocksänka

Literature

AS = Atlas över Sverige, utg. av Svenska Sällsk. f. Antropologi o Geografi.
BGIU = Bull. Geol. Inst. Upsala.
Biul. Peryglac. = Łodzkie towarzystwo naukowe, Sectio III, Biuletyn Peryglacialny.
GFF = Geol. Fören. i Stockholm Förhandl.
KSVAH = Kungl. Svenska Vetenskapsakad. Handl.
NGU = Norges Geologiske Undersøgelse.
SGU = Sveriges Geologiska Undersökning.

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